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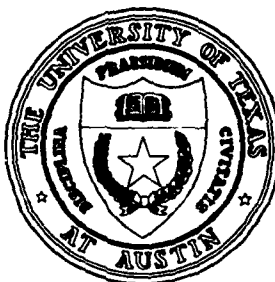
ANNUAL REPORT ON ELECTRONICS RESEARCH
AT THE UNIVERSITY OF TEXAS AT AUSTIN

For the period January 1, 1989 through December 31, 1989

JOINT SERVICES ELECTRONICS PROGRAM

Research Contract AFOSR F49620-89-C-0044

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December 31, 1989

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The Electronics Research Center at The University of Texas at Austin consists of interdisciplinary laboratories in which graduate faculty members, Master's and Ph.D. candidates from numerous academic disciplines conduct research. The disciplines represented in this report include information electronics, solid state electronics, and electromagnetics.

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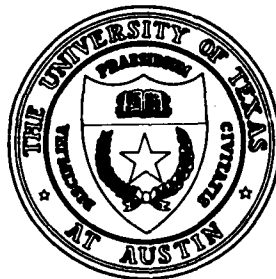
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DIRECTOR'S OVERVIEW
and
SIGNIFICANT ACCOMPLISHMENTS

DIRECTOR'S OVERVIEW

This report covers the twelve-month period January 1, 1989 to December 31, 1989. Of particular importance is the fact that it is the first Annual Report covering work done on the new contract AFOSR F49620-89-C-0044. The current JSEP program at The University of Texas at Austin is a relatively balanced program with five solid-state electronics research units, two in information electronics, and two in electromagnetics. The cornerstone of the program rests on solid-state electronics with five research units dedicated to III-V heterostructures. Reports on specific progress made during this first year are presented herein.

During the formulation of the JSEP proposal, which ultimately led to the current contract, great care was taken to form a synergistic program. Evidence of this synergism, not only between faculty within an area (e.g., solid-state electronics) but also across areas (e.g., electromagnetics and solid-state electronics), is presented in the following significant accomplishment involving molecular beam epitaxy with high-speed device applications and millimeter-wave monolithic array components. As a result of meaningful collaboration between different faculty concerned with semiconductor growth, semiconductor devices, and electromagnetics, significant progress has been made in improving the performance of the QWITT (quantum well injection transit time) diode. This device appears to offer significant potential as a self-oscillating mixer. Further details follow at the end of this overview.

Finally, we mention two items that favorably impact the JSEP program at The University of Texas at Austin. First, the new building to house microelectronics, materials science, engineering, and manufacturing engineering is well along in its construction. This new building will include approximately 12,000 square feet of clean space (including service aisles), approximately 15,000 square feet of testing and evaluation laboratory space, and office space for approximately 15 faculty and 120 graduate students involved in semiconductor research. We anticipate moving into this new building in the spring of 1991.

The second item is concerned with the Texas Advanced Technology and Research Program, which was funded at over \$60 million by the State Legislature in 1989. A total of 3,280 proposals were submitted by researchers within the state and 440 proposals were selected for funding. The selection was carried out by peer review including 125 scientists and engineers organized into 14 review panels. None of these individuals was in any way associated with a Texas college or university. Of the 440 proposals funded, 121 were at U.T. Austin, and of the 121 successful proposals at U.T. Austin, 6 were written by JSEP faculty. Dr. Itoh, Dr. Marcus, Dr. Neikirk, and Dr. Powers are the recipients of these grants, which total slightly more than \$1 million. We expect this infusion of state funds, on which there is no overhead, to have a positive synergistic impact on the U.T. JSEP program.

Edward J. Powers for the
U.T. JSEP faculty participants

Molecular Beam Epitaxy with High Speed Device Applications

Ben G. Streetman and Dean P. Neikirk

and

Millimeter-Wave Monolithic Array Components

Tatsuo Itoh and Dean P. Neikirk

The Joint Services Electronics Program

The University of Texas at Austin

There is considerable interest in developing quantum well devices for high frequency analog applications. Quantum well oscillators have been shown to be capable of generating power at high millimeter wave frequencies, and there is great expectation that these devices will serve as a useful local oscillator at frequencies between 100-1000 GHz. However, there is considerable debate over the quantum well device structures that must be used to maximize the output power obtained from these devices. There is also interest in exploring the possibility that these devices could be used as both a detector and an oscillator for use in highly sensitive receiver systems. In order to realize the potential of these devices, under JSEP support we have developed a truly collaborative effort between our semiconductor growth, semiconductor device, and electromagnetics research groups.

During the 1987 contract year we proposed an improved quantum well oscillator, the quantum well injection transit time (QWITT) diode, consisting of a double barrier structure coupled with a depletion region which increases the specific negative resistance and impedance of the device so that higher output power can be obtained. Our device models for the QWITT diode show that for a particular operating frequency and quantum well, there is an optimum length for the depletion region. During 1988 we began fabrication and testing of our device. Three structures consisting of identical quantum well regions but with three different drift region lengths of 500 Å, 1000 Å, and 2000 Å respectively, were examined. The heterolayers were grown in our Varian GEN II MBE system on n^+ GaAs substrates, and device mesas were defined using conventional

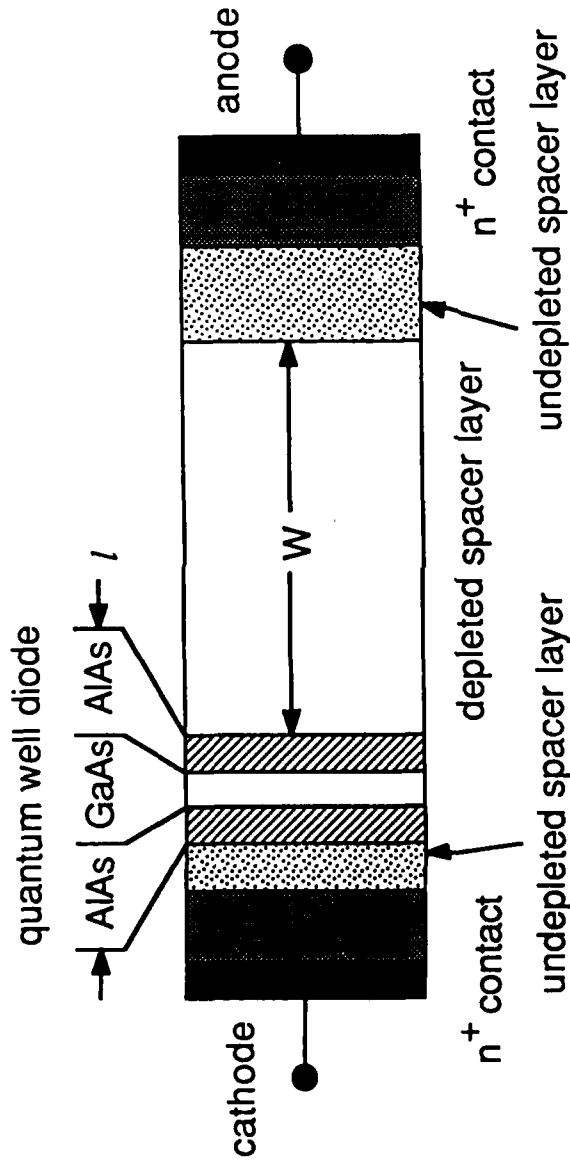
photolithographic techniques. This aspect of our work is supported by our JSEP Solid State Unit on Molecular Beam Epitaxy. Both dc and rf performance have been measured. For the different devices, as the length of the drift region is increased from 500 Å to 2000 Å, the microwave output power increased dramatically, as expected from our models which predicted an optimum depletion region length of 2000 Å for operation near 10 GHz. These were the first dc and rf results measured for the QWITT diode. The peak output power of ~ 1 mW in the frequency range of 2-8 GHz obtained here is still the highest output power ever achieved from any quantum well oscillator at any frequency.

During the 1988/89 period we continued the investigation of QWITT diodes. One advance made was the inclusion of a doping spike in the drift region, leading to reduced dc bias voltages. This allowed us to achieve the highest dc to rf conversion efficiency reported for a quantum well oscillator. We also investigated the use of a QWITT diode as a self-oscillating mixer. This aspect of our research has required strong coupling between the microwave circuit research done in our Electromagnetics Area and the device group in our Solid State Area. To test the operation of the QWITT as a self oscillating mixer we used both a rectangular metal waveguide circuit, which is relatively easy to construct for 10 GHz (X-Band) operation, and a microstrip planar circuit, which would be more appropriate for use in a monolithic millimeter wave integrated circuit (i.e. in MIMIC). The waveguide mixer exhibited a conversion gain of about 10 dB in a narrow bandwidth, and a conversion loss of about 3-5 dB over a broad bandwidth. A planar mixer circuit exhibited a narrow band conversion gain of 4 dB or a broad band conversion loss of 8-10 dB. To the best of our knowledge, this is the only report of conversion gain ever obtained from a self-oscillating mixer using a quantum well device, indicating the possibility of integration of mixer and LO functions.

The potential advantages of a self-oscillating mixer are significant. Firstly, all conventional mixers exhibit conversion loss, i.e. the IF output signal power is always less than the RF input signal power. Only self-oscillating mixers can show conversion gain,

where the IF power is larger than the RF input. Another advantage is the considerable reduction in receiver circuit complexity available with a self-oscillating mixer. In a conventional mixer there must be separate circuits for generating LO power and for combining the LO and RF signals at the mixer. The self-oscillating mixer inherently combines these two functions. Thus, the demonstration of conversion gain using a QWITT diode as a self-oscillating mixer is a significant step in the direction of the development of new microwave and millimeter wave receivers for radar and communications applications.

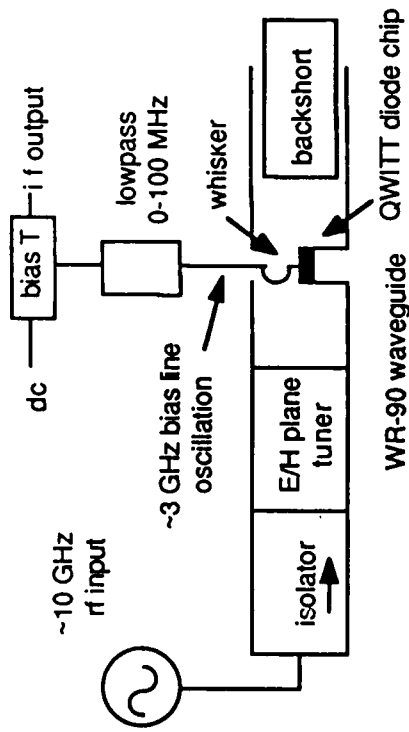
Quantum Well Diodes for High Frequency Applications



Quantum Well Injection Transit Time (QWITT) Diode:

- Critical dimensions only a few atomic layers thick
- Optimized "drift region" length W required for efficient microwave operation
- Molecular Beam Epitaxy used for materials growth
- Highest microwave output power from any quantum well diode

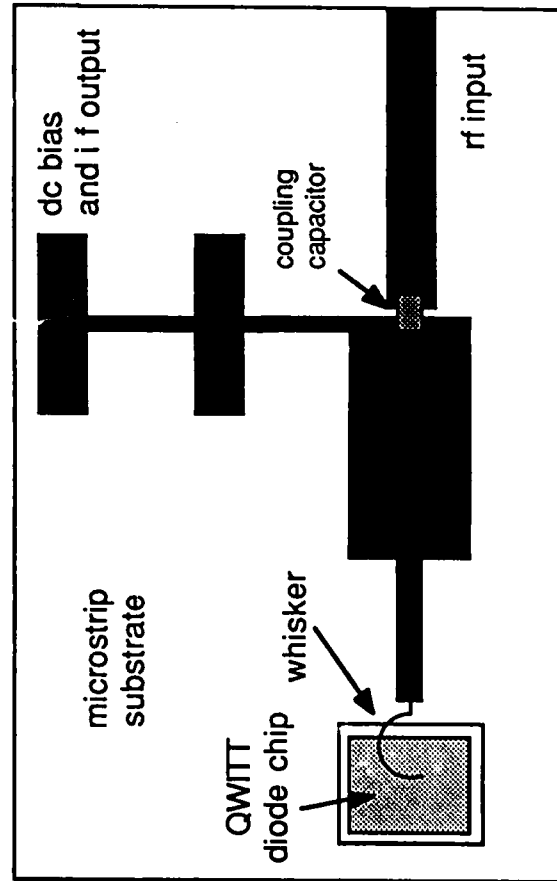
Quantum Well Diodes for High Frequency Applications



Waveguide Self-Oscillating Mixer

- 3rd harmonic operation at 9GHz
- 3dB broad band conversion loss
- 10dB conversion gain over narrow band

xix



Planar Self-Oscillating Mixer

- fundamental operation at 10GHz
- 8dB broad band conversion loss
- 4dB conversion gain over narrow band

I. INFORMATION ELECTRONICS

Research Unit IE89-1: Multi-Sensor Signal Processing

Principal Investigator: Professor J. K. Aggarwal (512) 471-1369

Graduate Students: S. Karthik and C. C. Chu

A. **SCIENTIFIC OBJECTIVES:** The overall scientific objective of this research unit is to develop algorithms for multi-sensor signal processing. Further, accurate sensor-scene and sensor-sensor relationship will be established based on the physical principles of signal generation, detection and interactions. We shall develop computer methods for concomitant analysis of information in signals from different sensors, and develop efficient and accurate techniques for signal processing and interpretation. In this research, the extraction of information from signals is to be accomplished by using Artificial Intelligence techniques and rule-based methods, so that information gathered from multiple sensors may be easily combined. The sensors to be used in the system will include visual, infrared, and range sensors, laser radar, and millimeter wave radar.

Signal processing that integrates multisensory data provides information that cannot be obtained by processing the data individually. By integrating information from different sensors, a more powerful and robust system may be built to interpret the scenes of interest. Also, rule-based methods can better implement the integration task among signal systems that do not have well-understood mathematical models. In addition, detailed analysis of signal generation process, transmission environment and data acquisition models is thoroughly investigated to find out the physical significance of the sensed signals. Thus more meaningful processing techniques can be designed based upon such knowledge.

There are a number of issues to be studied for a multi-sensor system, such as the relationship between different sensors, sensor behavior difference under different imaging conditions, spatial and temporal correspondence between signals, calibration and registration between various sensors, and the strategies for synergistically integration of the extracted information. The differences between the principles on how these sensor devices operate require that individual sensor system be analyzed, and accurate models be established for sensed signals. The strategies to combine the extracted information and to interpret them in a consistent way is critical to multi-sensor signal processing, and is a research area that has not yet been fully explored.

Traditionally, the extraction of information from single and multi-dimensional signals are done by filtering, statistical analysis, and pattern classification. In comparison, adequate attention has not been given to problems where the relationships between the signals and the system cannot be described in terms of mathematically well-understood formulations. Hence, there exists a need for the development of rule-based methods to model diverse mechanisms that generate and distort signals.

B. **PROGRESS:** A significant amount of research has been conducted in this research unit in the analysis and interpretation of multi-sensory signals. These signals are analyzed concomitantly to provide useful information regarding the sensed scene and its characteristics. In our research program, we are developing knowledge-based systems for object detection and image interpretation in various domains of applications. The emphasis on information integration from

multiple sensors and detecting man-made objects in images of outdoor scenes. We have two projects under development: (1) the integrated thermal and visual image synthesis system and (2) intelligent integration of information from laser radar for man-made objects detection and recognition.

The ideas common to both projects are: (a) to study the physical models of the imaged objects and individual sensors, and (b) to integrate information derived from various sensors. We have approached the problem as follows. First, physical models for signal generation, transmission, and acquisition are studied, leading to a better understanding of fundamental properties of images and the development of effective algorithms. Second, information integration is used to resolve ambiguities that cannot be dealt with in mono-sensor operation. This integration is not a simple concatenation of sets of data, but rather a synergistic integration. Interactions between sensors has to be studied to derive features that are not readily available.

The approaches and results of individual projects are outlined here. For the thermal and visual image synthesis project, the octree data structure is used to model 3D objects. Heat flows within objects are simulated. The resulting surface temperature variation is used to create the thermal image. Cavities within vehicles and the heat generation by engines are also modelled to provide more realistic thermal images. The octree structure also facilitates the generation of the corresponding visual images. For the LADAR project, surface fitting and image statistics are used to segment images. Low-level information fusion is used to improve segmentation. A knowledge-based system is used to achieve object classification and scene interpretation. The progress of both projects are summarized in the following.

Thermal and Visual Image Synthesis

The development of our integrated thermal and visual image synthesis system is within a larger framework of scene interpretation using both thermal and visual images and a sensor fusion approach. In the past, we have established a prototype system for scene interpretation which relies on image segmentation and understanding the physics of individual sensors. A scene segmentation system that uses both thermal and visual information has been built in the past. The thermal and visual image synthesis system is constructed to verify the analysis framework established in previous works of this unit.

The analysis framework can be summarized as the following [1]. The thermal behavior of scene objects is studied in terms of surface heat fluxes. The thermal image is used to estimate surface temperature, and the visual image provides information about surface absorptivity and relative surface orientation. We can compute relative surface orientation by approximating surface reflectivity as opaque and Lambertian. The absorbed heat flux is computed using estimates of surface reflectivity, relative orientation, and the intensity and direction of solar irradiation. The convection heat flux is obtained from available empirical correlations. The radiation heat loss from object surface is computed using the Stefan-Boltzmann law. Subtracting the convected and radiated heat fluxes from the absorbed heat flux gives us the "conducted" heat flux. The ratio of conducted heat flux to absorbed heat flux describes the imaged objects' relative ability to sink or source heat. This ratio depends largely on the normalized lumped thermal capacitance of the imaged objects. Thus, features based on these estimates of heat fluxes serve as meaningful on specific descriptors of imaged objects. The approach has been successfully tested on real data obtained from outdoor scenes [1,2].

We have developed a unified approach for modelling objects which are imaged by thermal (infrared, IR) and visual cameras based on the physical principles described above. The model supports the generation of both infrared ($8\mu\text{m}$ - $12\mu\text{m}$ wavelength) images and monochrome visual images under a variety of viewing and ambient scene conditions. An octree data structure is

used for object modelling. The octree serves two different purposes - (1) surface information is encoded in boundary nodes and efficient tree traversal algorithms facilitate the generation of monochrome visual images, and (2) the compact volumetric representation facilitates simulation of heat flow in the object which gives rise to surface temperature variation, which in turn is used to synthesize the thermal image. The developed techniques may be used in a model-based scene interpretation system which analyzes concomitantly thermal and visual images of scenes.

Thermal behavior of an object is estimated by using a model which is based on the thermal characteristics of the object (e.g., absorptivity, convection heat transfer coefficient and thermal conductivity) and the thermal parameters of its surroundings (e.g., wind speed, the direction of solar irradiation, the ambient temperature, etc.) The entire body of the modelled object is assumed to be homogeneous. Surface temperature of an object is calculated for each node of the octree under the assumption that an equilibrium exists (1) between the heat flux flowing into the surface of the object and those flowing out from the surface, and (2) between the adjacent nodes. First, the octree structure is modified to represent thermal characteristics and to encode explicitly the node-adjacency information for each node. For each node of the octree, the conduction, convection and radiation heat fluxes and solar irradiation are calculated. The balance between these heat flows and the internal energy variation of the node is described quantitatively to form a set of equation which is calculated using numerical techniques.

The resulting variation of the surface temperature is mapped into different intensity values and each node is projected onto the image plane with the corresponding intensity value. This simulates the imaging processes of thermal (infrared) images. Also, the ratio of conducted heat flux to absorbed flux, which has been shown to facilitate the identification of different classes of objects in outdoor scenes, is computed at the surface nodes of the modelled object. Our implementation of the proposed technique shows results which are comparable to the information obtained from experiments [1]. Even though the effect due to atmospheric attenuation is not considered in our model, it is justified for imaging distances of a few hundred meters and sensing wavelength band of $8\mu\text{m}$ - $12\mu\text{m}$.

We have made extensions to the above approach by adding the ability to model non-homogeneous 3D objects. Real-world objects are not homogeneous in the form of internal cavities, material differences, and sources of heat generation (e.g., engine in vehicles). The thermal images of objects with non-homogeneous interior is quite different from the one generated by assuming a solid, homogeneous object. An octree of the simulated object is first constructed from multiple silhouettes. Then the cavity and heat generation are specified by giving multiple sectional views. An octree for the non-homogeneity is constructed from multiple sectional views. These two octrees are then intersected and the thermal properties of the nodes corresponding to the non-homogeneity in the main octree are updated. This procedure is applied to cavity as well as heat generation. Once the octree for the non-homogeneous object is constructed, thermal simulation is performed as described earlier to generate thermal images. An octree with a better surface normal encoding technique called *volume surface octree* (vs-octree) is used. An implicit finite difference technique as opposed to the explicit method used in earlier work is used for thermal simulation.

The vs-octree used in this work has two advantages over the octree used in the earlier work [3]. The first advantage is that the surface encoding technique used in the vs-octree results in finer quantization of the surface normals as compared to the earlier approach. This improves the quality of the visual image generated. The accuracy of the thermal simulation is also improved due to the fact that surface normals are used in the computation of the absorbed solar irradiation. The second advantage of the vs-octree is that the object is decomposed into numerous small surface nodes and internal nodes as opposed to large surface nodes in the earlier approach. This results in improved accuracy of the computed surface temperatures as the temperature of a small

surface node corresponds exactly to the surface temperature. Whereas, the temperature of a large surface node does not correspond to the surface temperature alone, but represents some combination of surface and interior temperatures.

The vs-octree of an object can be constructed from multiple views of the object. For each view, the contour is smoothed by a tension spline. Then, a quadtree is constructed for each view which stores the information pertaining to the contour. The quadtrees from multiple views are then intersected to obtain the vs-octree. The surface normals of the surface nodes in the vs-octree are computed based on the contour normals in the quadtrees. To incorporate a cavity in the object, the thermal properties are changed to that of air. To model heat sources, a constant volumetric heat generation rate is specified in the nodes pertaining to the heat source. These extensions result in realistic and accurate thermal images. Thermal images of different objects with cavity and heat generation were generated. It was observed that the generated thermal images were quite different from the ones generated assuming a homogeneous object. The heat flux ratio described earlier were also computed. It was observed that the heat flux ratio was the highest for a solid object and lowest for an object with cavity and heat generation. These results were consistent with the observations in [1].

Since the proposed system is based on 3D models of thermal behavior of an object, it offers several advantages over facet-based approaches [4] for thermal image synthesis. This system allows for effects of lateral heat flow in the surface and also heat flow into the object. Besides, this system does not require large data files of geometric and thermal parameters which is needed by facet-based systems. This system will be used in a model-based vision system which interprets thermal and visual images. Each class of objects to be classified will be represented by distinct octree models. The specification of a unique model for each class of objects to be recognized in the scene allows for more accurate prediction of thermal images of objects and also allows for the prediction of the values of discriminatory features which can be used in classification. Simulations of heat flows on this model yields thermal images specific to scene conditions. These generated images and the discriminatory features calculated in the simulation will be used to identify objects belonging to that particular class.

Intelligent Integration of Information from Laser Radar and Other Special Sensors

Laser radar (LADAR) systems have received much attention in recent years. LADAR gives range, intensity (also known as the reflectance component), and velocity images simultaneously. The velocity image is generated by using Doppler Effect. The LADAR image data are extremely noisy. We are interested in using LADAR images to detect and recognize man-made objects in outdoor scenes. Our approach is to segment individual LADAR image components first, then we integrate the results from multiple segmentation maps. The final integrated segmentation provides the basis of image interpretation. Our first objective of this work is to separate man-made (MMO) objects from background, which has been achieved. The second, and current, objective is to interpret the segmented scene by using a knowledge-based system (KBS). Preliminary results that demonstrate improved scene segmentation by integrating multiple components of LADAR data [5] has been accepted for publication. A knowledge-based system is developed using KEE, an expert system shell, for intelligent system development.

The range image is segmented by surface fitting to explore the geometric characteristics of object surface. The range segmentation module tends to find smooth fit for man-made objects. Because of the noise and irregularities of shapes, objects in the background, e.g., trees, shrubs, usually cannot be fitted with planar surfaces. The intensity data is segmented based on the mean and standard deviation of the image pixel values. For objects with same surface characteristics (say, metallic body), the areas occupied by the object on the intensity image are likely to present

approximately the same degree of busyness. We have found that the statistical method, if applied to the range data, can also provide good segmentation cues that is complementary to the results from the surface fitting method. The velocity component is useful when the objects are moving. The processing of velocity components proceeds along the line of processing range images.

Next, we combine various segmentation maps from different data channels and processed by different methods to produce a single integrated segmentation map. A segment is established with high credit, if both segmentation maps on range image and intensity image generate about the same segmentation. Otherwise, the segment is either cancelled or degraded to a lower credit, if the two segmentation maps contradict each other. The integrated segmentation results are compared with those obtained by human interaction. The two segmentation maps show strong resemblance to each other and share nearly coincident contours. After the segmentation maps are effectively integrated, the new map is used to verify individual segmentation maps, and to provide cues to segmentation modules for refinement.

We have built a prototype knowledge-based scene interpretation system [6] that incorporates reasoning. Each region in the segmented scene is analyzed and given a label. The interpretation system posts hypotheses about the scene and use available data to verify or reject these hypotheses. Other signal sources, such as Infrared (FLIR) sensors and millimeter wave radars (MMW), can also be incorporated into the system as independent knowledge source modules. The knowledge-based system consists of three major components: the knowledge bases, the data bases, and the inference engine. In our work, the inference engine is provided by KEE. The interpretation strategy used in this work follows the paradigm of Clancey's Heuristic Classification [7]. First, numerical parameters are converted into qualitative descriptors, and these descriptors are used to generate intermediate classifications of segments as MMO or background objects (BG). Segments are grouped into objects and these objects are further classified into one of the pre-defined categories. The knowledge of image interpretation is coded as KEE rules. The reasoning process is driven in the forward chaining mode.

Four types of knowledge are used to construct these interpretation rules. The first source of knowledge comes from the numerical measurements for each segment and object. This is the knowledge derived from pixel values of input images. The second source of knowledge comes from the neighborhood relationships in the segmentation map. The third type of knowledge comes from the models of potential targets. The last type of knowledge is "common sense" and domain-dependent assumptions that provide guidance to the reasoning process. Each KEE rule posts one or more hypotheses, which are expressed as a quadruple of (*segment/object, attribute, value, confidence factor*). The confidence factor is a real number between -1.0 and 1.0 to denote the degree of disbelief (negative numbers) or belief (positive numbers) of the associated hypothesis. This is necessary because all the rules are not equally effective in all the circumstances. The same rule may generate the same hypothesis with different confidence factors when the attributes of the segments under consideration are different.

In a limited test sets, the KBS is able to detect all man-made objects, and correctly recognize most targets articulated in a broad-sided view toward the sensor. The length, speed, body dimensions of the detected vehicles are usually correctly estimated using information of the spatial resolution of the LADAR images. Since the current target modeling emphasizes only the contour of the target, which is aspect-sensitive, recognition under general aspect (rotations) is not feasible. Currently, effort is being devoted to the development of a larger library of 3D models of military vehicles with relevant features that are detectable in LADAR, thermal, MMW radar and visual imagery.

We have acquired one set of FLIR data from the Army Night Vision Laboratory this year and plan to incorporate FLIR data into our LADAR-based image interpretation system. We expect to develop algorithms that can integrate information from multiple types of sensors and detect

objects in difficult imaging conditions. With (1) better understanding of sensor physics, (2) different signal processing and segmentation techniques applied on different information sources, and (3) effective methods of information integration, we expect to achieve better scene analysis and object classification than conventional algorithms. The final scene interpretation is aimed to (1) classify segments as different types of objects, (2) generate a complete interpretation of the scene, and (3) pinpoint a *most interesting region* to human operator or other control systems. In particular, segmentation and recognition of objects of relevance and interests to the Department of Defense in thermal, visual, and radar images are the ultimate goals for all projects of this unit.

C. FOLLOW-UP STATEMENT: Past research conducted by this research unit in the analysis and processing of signals from different sensors has demonstrated that multi-sensor fusion is a powerful approach for signal processing and interpretation. Detailed signal modeling based on physical principles and field observations will be undertaken to derive more effective signal processing techniques. This unit will pursue both the investigation of scientific issues and the development of engineering solutions to the practical problems. This research will allow for the design of general, robust systems for signal interpretation that can take the advantage of multiple information sources.

D. REFERENCES:

1. N. Nandhakumar and J.K. Aggarwal, "Integrated Analysis of Thermal and Visual Images for Scene Interpretation," *IEEE Trans. on Pattern Analysis and Machine Intelligence*, Vol. PAMI-10, No. 4, pp.469-481, July 1988.
2. N. Nandhakumar and J.K. Aggarwal, "Multisensor Integration - Experiments in Integrating Thermal and Visual Sensors," *Proc. of First International Conference on Computer Vision*, London, England, pp. 83-92, June 1987.
3. C. Oh, N. Nandhakumar, and J. K. Aggarwal, "Integrated Modelling of Thermal and Visual Image Generation," *Proc. IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, San Diego, CA, June 1989.
4. G. Gerhart, G. Martin, and T. Gonda, "Thermal Image Modelling," in the *Proceedings of SPIE Conference on Infrared Sensors and Sensor Fusion*, vol. 782, pp.3-9, 1987.
5. C. C. Chu, N. Nandhakumar, and J. K. Aggarwal, "Image Segmentation Using Laser Radar Data," to appear in *Pattern Recognition*.
6. C. C. Chu, N. Nandhakumar, and J. K. Aggarwal, "Integrating Segmented Laser Radar Images Using a Knowledge-Based System", in the *Proceedings of SPIE Sensor Fusion - II conference*, Philadelphia, Pennsylvania, November 6-9, 1989.
7. W. J. Clancey, "Heuristic Classification," *Artificial Intelligence*, vol. 27, pp.289-350.

I. LIST OF PUBLICATIONS (Those supported by JSEP are marked with *)

- * C. C. Chu, N. Nandhakumar, and J. K. Aggarwal, "Image Segmentation Using Laser Radar Data," to appear in *Pattern Recognition*.

J. K. Aggarwal and N. Nandhakumar, "On the computation of motion from sequences of images -- A review," *Proceedings of the IEEE*, Vol. 76, no. 8, pp. 917-935, August 1988.

D. C. Baker, S. S. Hwang, and J. K. Aggarwal, "Detection and segmentation of man-made objects in outdoor scenes: concrete bridges," *J. Opt. Soc. Amer. A.*, vol. 6, no. 6, pp. 938-950, June 1989.

C. H. Chien and J. K. Aggarwal, "Model construction and shape recognition from occluding contours," *IEEE Trans. on Pattern Analysis and Machine Intelligence*, vol. 11, no. 4, pp. 372-389, April 1989.

Wang, Y. F., and J. K. Aggarwal, "Integration of active and passive sensing techniques for representing three-dimensional objects," *IEEE Trans. on Robotics and Automation*, vol. 5, no. 4, pp. 460-471, August 1989.

II. LIST OF CONFERENCE PROCEEDINGS (Those supported by JSEP are marked with *)

- * C. C. Chu, N. Nandhakumar, and J. K. Aggarwal, "Integrating Segmented Laser Radar Images Using a Knowledge-Based System", in the *Proceedings of SPIE Sensor Fusion - II conference*, Philadelphia, Pennsylvania, November 6-9, 1989.

- * C. Oh, N. Nandhakumar, and J. K. Aggarwal, "Integrated modelling of thermal and visual image generation," in *Proc. IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, San Diego, California, June 1989.

J. K. Aggarwal, "Issues in AI and computer vision," IEEE Computer Society Workshop on Artificial Intelligence and Computer Vision, San Diego, California, June 1989.

J. K. Aggarwal, "Multisensor Computer Vision -- Issues and Results," NATO Advanced Research Workshop on Multisensor Fusion for Computer Vision, Grenoble, France, June 1989.

X. Lebeque, D. C. Baker, and J. K. Aggarwal, "2D and 3D model based recognition of man-made objects in outdoor scenes," *Proc. 6th Scandinavian Conference on Image Analysis*, Oulu, Finland, June 1989.

Y. F. Wang, J. K. Aggarwal, "Geometric modeling using both active and passive sensing," *Proc. 2nd Sensor Fusion Conference: Spatial Reasoning and Scene Interpretation*, Cambridge, MA, November 1988.

III. EDITOR OF BOOKS, CHAPTERS OF BOOKS

C. H. Chien and J. K. Aggarwal, "3D Structures from 2D Images," in *Advances in Machine Vision*, Jorge Sanz, Ed., Springer-Verlag, 1989.

IV. LIST OF THESES AND DISSERTATIONS (Those supported by JSEP are marked with *)

- * Asar, Harish, "Pyramid-Based Image Segmentation Using Multisensory Data," graduated September 1988
- * Oh, Chanhee, "Integrated Modelling of Thermal and Visual Image Generation," graduated May 1989.

Baker, David C., "Incremental Segmentation for Interpretation of Man-Made Objects in Color Images of Non-Urban Scenes: Concrete Bridges," graduated May 1989.

V. GRANTS AND CONTRACTS

National Science Foundation Grant DCR-8517583, "Space Perception from Multiple Sensing," Professor J. K. Aggarwal, Principal Investigator.

National Science Foundation Grant ECS-8513123, "Analysis and Reconstruction of Three-Dimensional Microscopic Images," Professor J. K. Aggarwal, Principal Investigator and Professors A. Bovik and K. Diller, Co-Principal Investigators.

Army Research Office Contract DAAL03-87-K-0089, "Synergetic Multisensor Fusion," Professor J. K. Aggarwal, Principal Investigator.

Research Unit IE89-2: NONLINEAR ESTIMATION AND STOCHASTIC
ADAPTIVE CONTROL

Principal Investigator: Professor S. I. Marcus (471-3265)

Graduate Students: Emmanuel Fernández-Gaucherand and Enrique Sernik

A. SCIENTIFIC OBJECTIVES: This research unit is concerned with novel methods of extracting information from noisy measurements of the state of a nonlinear stochastic system, for the purpose of real time estimation or control. The problem of nonlinear state estimation is concerned with the extraction of information about the state of a nonlinear stochastic dynamical system from nonlinear noisy measurements. The state cannot be observed directly; instead, we have access to an observation or measurement process which is contaminated by noise and which is related to the state via a stochastic model. The objective is the calculation of either the entire conditional distribution of the state given the past measurements or some particular estimate, such as the conditional mean. In addition, it is desired that the state estimate or conditional distribution be calculated recursively; that is, the observations are being received continuously, and it is required that the estimate be continuously revised to take into account the new data. Thus the state estimate is generated by passing the measurements through a filter or estimator. The basic objective here is the study of the design, analysis, and implementation of high-performance optimal and suboptimal estimators which operate recursively in real time.

Adaptive control refers to the control or regulation of a system in the presence of parameters which are unknown or which vary with time. Some type of monitoring of the system's behavior, followed by a suitable control action, is referred to as an adaptive controller. In this research unit, systems which also are affected by noise disturbances, and in which the state of the system is not measured exactly, will be considered. The objective is that of designing and analyzing a control law (or feedback controller) which minimizes a given cost or tracks a given reference signal in the presence of unknown parameters, noise, and incomplete (or noisy) state observations.

Systems in which changes can occur which are more drastic than relatively slow parameter variations are exemplified by systems with failure modes which significantly alter the structure of the system. Reconfigurable aircraft represent one such type of system. In this case, there is a "hybrid" situation in which the state of the system consists of a set of real numbers (the usual "state") together with a set of discrete or Boolean variables (describing, for example, the structure of the system). One eventual result of research on this class of systems will be higher level symbolic modules which will work with lower level adaptive controllers to form a more intelligent multi-level control system.

B. PROGRESS: As proposed in our triennial proposal, we have investigated several problems in the area of discrete event systems, in order to develop the capability for analyzing multi-level systems which can intelligently process different types of information. In discrete event systems, examples of which include flexible manufacturing systems and computer networks, the state of the system changes at asynchronous discrete instants of time instead of continuously and is governed by the intricate interaction of discrete events. Models and control algorithms have begun to be developed by modeling the discrete event dynamical system (or plant) as a finite

automaton with certain controllable events, the occurrence of which can be disabled by means of a control action. A number of such problems are understood and have been solved in the case that the supervisor (or controller) can perfectly observe the occurrence of events in the plant [1], but the more interesting case of the supervisor receiving incomplete information is less well understood. In many cases, this can be modeled by constructing a mask, or observation function, M , through which the supervisor observes the occurrence of events; hence, certain events cannot be distinguished from each other or cannot be seen by supervisors. In this case, necessary and sufficient conditions for the closed-loop behavior or language L to be realized by the construction of a suitable supervisor are known for some problems of interest [2]. As opposed to the much simpler case of perfect information, it turns out that the class of sublanguages $\mathcal{I}(L)$ of a given language L which satisfy the necessary and sufficient conditions do not necessarily possess supremal elements; thus, minimally restrictive solutions may not exist. Therefore we are forced to resort to a solution that is minimally restrictive in some narrower sense. On the other hand, there is a smaller class of sublanguages $\mathcal{Q}(L)$ which is algebraically well-behaved and does possess a supremal element. In [3], we show that the supremal element of this class can be computed via an algorithm which has a simple graphical structure and is well suited to computer implementation; this algorithm recursively removes edges and nodes from the graph of an automaton which generates a particular language. These algorithms provide a good suboptimal solution to the problem; in addition, they involve new classes of automata which are of interest in their own right. In some cases, however, this suboptimal solution is too restrictive, and it is natural to study maximal elements of $\mathcal{I}(L)$. This is a much more difficult problem, but we have been able in [4] to develop an algorithm which computes such a maximal element as a limit of a decreasing sequence of sublanguages of L .

In [5], we study supervisor synthesis problems for discrete event systems by means of the synchronous composition of the plant and the supervisor. We present a new algorithm for the construction of the minimally restrictive supervisor in the case of complete observations; this algorithm is computationally more efficient than any discovered by other researchers. In addition, closed form representations are derived for supremal controllable and supremal observable sublanguages.

We have undertaken an in-depth investigation of adaptive nonlinear estimation problems for stochastic systems involving incomplete (or noisy) observations of the state and unknown parameters. In [6] and [7], the adaptive estimation of the state x_t of a finite state Markov chain with incomplete state observations y_t taking values in a finite set, and in which the state transition probabilities depend on unknown parameters, is studied. Such problems arise in systems such as computer communication networks. In general, the adaptive estimation problem involves the computation of estimates (e.g., state estimates) in the presence of unknown parameters; in addition, estimates of the parameters are computed simultaneously. In the present context, the adaptive estimation problem is that of computing recursive estimates of the conditional probability vector of the state x_t given the past observations $\{y_0, \dots, y_t\}$, when the state transition matrix Q is not completely known (i.e., it depends on a vector of unknown parameters θ — this dependence is expressed as $Q(\theta)$).

The approach to this problem which we have investigated has been widely used in linear filtering: we use our previously derived recursive filter [8] for the conditional probabilities with known parameters, and we simultaneously recursively estimate the parameters, plugging the parameter estimates into the filter. This adaptive estimation algorithm is then analyzed via the Ordinary Differential Equation (ODE) Method [9], [10]. That is, it is shown that the convergence of the parameter estimation algorithm can be analyzed by studying an averaged ordinary differential

equation. The most crucial and difficult aspect of the proof is that of showing that, for each value of the unknown parameter, an augmented Markov process has a unique invariant measure. New techniques for the analysis of the ergodicity of time-varying Markov chains are utilized. The convergence of the recursive parameter estimates is studied, and the optimality of the adaptive state estimator is proved. This is the first such analysis of an adaptive nonlinear estimation problem in the literature.

In a natural extension of our work in [6],[7], we have begun to apply similar techniques to some interesting stochastic control problems involving finite state Markov processes with incomplete observations and unknown parameters. One intriguing set of problems for which some results are available when the parameters are known are those involving quality control and machine replacement; we study the properties of these problems in [11], with the eventual aim of developing optimal adaptive stochastic controllers. However, the presence of feedback makes this stochastic adaptive control problem much more difficult than the adaptive estimation problem of [6],[7]. We concentrate in [11] on the adaptive control of a problem with simple structure: the two-state binary replacement problem. An adaptive control algorithm is defined, and it is shown that the relevant augmented closed-loop Markov process is ergodic. This represents a crucial step toward the application of the ODE method and the solution of the adaptive control problem.

Another crucial step in the solution of this partially observed adaptive control problem is the development of better results on stochastic control with known parameters but partial state observations. Such results are proved in some generality in [12], in which we present sufficient conditions for a bounded solution to the average cost optimality equation to exist, in the case of countable state and observation spaces. These results are illustrated in the context of machine replacement problems. Structural properties for average cost optimal policies are obtained for a two state replacement problem. In addition, the sensitivity of the optimal cost and policy with respect to parameters of the machine replacement model is studied in [13].

In related work on adaptive Markov decision processes, the important issue of implementation has been addressed in [14], which presents finite-state discretization procedures for discrete-time, infinite horizon, adaptive Markov control processes which depend on unknown parameters. The discretizations are combined with a consistent parameter estimation scheme to obtain uniform approximations to the optimal value function and asymptotically optimal adaptive control policies. The adaptive control of systems with unknown disturbance distribution has been addressed in [15], in which we have extended the nonparametric results of [16] to problems with incomplete state observations. Our approach combines convergence results for empirical processes and recent results on parameter-adaptive stochastic control problems.

In order to deepen our insight into the types of nonlinear systems which occur in problems of nonlinear estimation and adaptive control, we have also investigated and solved a number of problems in the linearization of discrete-time and discretized nonlinear systems. Feedback linearization is a very effective control technique, when applicable. However, a digital feedback law is inevitable in practice, and discretization can destroy linearizability [17]. This is because the control input is constant between the sampling times. In [17], we investigate the effect of sampling on linearization for continuous time systems. It is shown that the discretized system is linearizable by state coordinate change for an open set of sampling times if and only if the continuous time system is linearizable by state coordinate change. Also, it is shown that linearizability via digital feedback imposes highly nongeneric constraints on the structure of the plant, even if this is known to be linearizable with continuous-time feedback.

C. FOLLOW-UP STATEMENT: The research described above will be actively continued under JSEP sponsorship. Some particular directions are the following. The stochastic adaptive control problem of [11],[12] will be further analyzed to establish convergence of the parameter estimates

and average cost optimality; in addition, another parameter estimation scheme based on the maximum likelihood technique is being studied. Our work [6],[7] on adaptive estimation of Markov chains with incomplete observations will be extended to include rate of convergence results and the tracking of time-varying parameters, as well as to include other types of observations. Also, our work [3]-[5] on discrete event dynamical systems will be continued; topics being investigated include stability, decentralized control, and the use of decomposed Petri net models.

D. REFERENCES:

1. P.J. Ramadge and W.M. Wonham, "Supervisory Control of a Class of Discrete-Event Processes," SIAM J. Control and Optimization, **25**, pp. 206-230 (1987).
2. R. Cieslak, C. Desclaux, A. Fawaz and P. Varaiya, "Supervisory Control of Discrete Event Processes with Partial Observations," IEEE Transactions on Automatic Control, **33**, pp. 249-260 (1988).
3. H. Cho and S.I. Marcus, "On Supremal Languages of Classes of Sublanguages that Arise in Supervisor Synthesis Problems with Partial Observation," Mathematics of Control, Signals, and Systems, **2**, pp. 47-69 (1989).
4. H. Cho and S.I. Marcus, "Supremal and Maximal Sublanguages Arising in Supervisor Synthesis Problems with Partial Observations," Mathematical Systems Theory, to appear.
5. V. Garg, R. Kumar, and S.I. Marcus, "Supervisory Control of Discrete Event Systems: Supremal Controllable and Recognizable Languages," Proceedings of the 27th Annual Allerton Conference on Communication, Control, and Computing (September 27-29, 1989).
6. A. Arapostathis and S.I. Marcus, "Analysis of an Identification Algorithm Arising in the Adaptive Estimation of Markov Chains," Mathematics of Control, Signals, and Systems, **3**, pp. 1-29 (1990).
7. A. Arapostathis and S.I. Marcus, "Adaptive Estimation of Markov Chains with Incomplete Information, in Analysis and Control of Linear Systems, C.I. Byrnes, et.al. Eds. Amsterdam: North-Holland, pp. 3-12 (1988).
8. K. Hsu and S.I. Marcus, "A General Martingale Approach to Discrete Time Stochastic Control and Estimation," IEEE Transactions on Automatic Control, **24**, pp. 580-583 (1979).
9. H. J. Kushner and A. Shwartz, "An Invariant Measure Approach to the Convergence of Stochastic Approximations with State Dependent Noise," SIAM Journal of Control, **22**, pp. 13-27 (1984).
10. L. Ljung and T. Soderstrom, Theory and Practice of Recursive Identification. Cambridge, MA: MIT Press (1983).

11. E. Fernandez-Gaucherand, A. Arapostathis and S.I. Marcus, "On the Adaptive Control of a Partially Observable Markov Decision Process," Proceedings of the 27th IEEE Conference on Decision and Control, Austin, TX (December 7-9, 1988).
 12. E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "On Partially Observable Markov Decision Processes with an Average Cost Criterion," Proceedings of the 28th IEEE Conference on Decision and Control, Tampa, FL (December 13-15, 1989).
 13. E. Sernik and S.I. Marcus, "Comments on the Sensitivity of the Optimal Cost and Policy for a Discrete Markov Decision Process," Proceedings of the 27th Annual Allerton Conference on Communication, Control, and Computing (September 27-29, 1989).
 14. O. Hernández-Lerma and S.I. Marcus, "Discretization Procedures for Adaptive Markov Control Processes," Journal of Mathematical Analysis and Applications, 137, pp. 485-514 (1989).
 15. O. Hernández-Lerma and S. I. Marcus, "Nonparametric Adaptive Control of Discrete Time Partially Observable Stochastic Systems," Journal of Mathematical Analysis and Applications, 137, pp. 312-334 (1989).
 16. O. Hernández-Lerma and S.I. Marcus, "Adaptive Policies for Discrete-Time Stochastic Systems with Unknown Disturbance Distribution," Systems and Control Letters, 9, pp. 307-315 (1987).
 17. A. Arapostathis, B. Jacubczyk, H.G. Lee, S.I. Marcus, and E.D. Sontag, "The Effect of Sampling on Linear Equivalence and Feedback Linearization," Systems and Control Letters, to appear.
- I. LIST OF PUBLICATIONS (*JSEP supported in whole or in part)
- * H. Cho and S.I. Marcus, "On Supremal Languages of Classes of Sublanguages that Arise in Supervisor Synthesis Problems with Partial Observation," Mathematics of Control, Signals, and Systems, 2, pp. 47-69 (1989).
 - * O. Hernández-Lerma and S. I. Marcus, "Nonparametric Adaptive Control of Discrete Time Partially Observable Stochastic Systems," Journal of Mathematical Analysis and Applications, 137, pp. 312-334 (1989).
 - * O. Hernández-Lerma and S.I. Marcus, "Discretization Procedures for Adaptive Markov Control Processes," Journal of Mathematical Analysis and Applications, 137, pp. 485-514 (1989).
 - * A. Arapostathis and S.I. Marcus, "Analysis of an Identification Algorithm Arising in the Adaptive Estimation of Markov Chains," Mathematics of Control, Signals, and Systems, 3, pp. 1-29 (1990).
 - * H. Cho and S.I. Marcus, "Supremal and Maximal Sublanguages Arising in Supervisor Synthesis Problems with Partial Observations," Mathematical Systems Theory, to appear.

- * A. Arapostathis, B. Jacubczyk, H.G. Lee, S.I. Marcus, and E.D. Sontag, "The Effect of Sampling on Linear Equivalence and Feedback Linearization," Systems and Control Letters, to appear.

II. LIST OF CONFERENCE PROCEEDINGS (*JSEP supported in whole or in part)

- * E. Sernik and S.I. Marcus, "Comments on the Sensitivity of the Optimal Cost and Policy for a Discrete Markov Decision Process," Proceedings of the 27th Annual Allerton Conference on Communication, Control, and Computing (September 27-29, 1989).
- * V. Garg, R. Kumar, and S.I. Marcus, "Supervisory Control of Discrete Event Systems: Supremal Controllable and Recognizable Languages," Proceedings of the 27th Annual Allerton Conference on Communication, Control, and Computing (September 27-29, 1989).
- * E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "On Partially Observable Markov Decision Processes with an Average Cost Criterion," Proceedings of the 28th IEEE Conference on Decision and Control, Tampa, FL (December 13-15, 1989).

III. LIST OF PRESENTATIONS (*JSEP supported in whole or in part)

- * S. I. Marcus, "Modeling and Control of Discrete Event Dynamic Systems" (Invited Plenary Lecture), SIAM Conference on Control in the 90's, San Francisco, CA, May 17-19, 1989.
- * E. Sernik and S.I. Marcus, "Comments on the Sensitivity of the Optimal Cost and Policy for a Discrete Markov Decision Process," Proceedings of the 27th Annual Allerton Conference on Communication, Control, and Computing, September 27-29, 1989.
- * V. Garg, R. Kumar, and S.I. Marcus, "Supervisory Control of Discrete Event Systems: Supremal Controllable and Recognizable Languages," Proceedings of the 27th Annual Allerton Conference on Communication, Control, and Computing, September 27-29, 1989.
- * E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "On Partially Observable Markov Decision Processes with an Average Cost Criterion," Proceedings of the 28th IEEE Conference on Decision and Control, Tampa, FL, December 13-15, 1989.
- * S.I. Marcus, "Toward the Adaptive Control of Partially Observed Markov Processes," Rice University, Houston, TX, November 18, 1989.
- * S.I. Marcus, "Toward the Adaptive Control of Partially Observed Markov Processes," Princeton University, Princeton, NJ, November 29, 1989.

IV. LIST OF THESES AND DISSERTATIONS

None

(Page 7, Res. Unit IE89-2, "Nonlinear Estimation and Stochastic Adaptive Control")

V. CONTRACTS AND GRANTS

Air Force Office of Scientific Research, Grant AFOSR-86-0029, "Research in Adaptive and Decentralized Stochastic Control," S.I. Marcus and A. Arapostathis, Principal Investigators, November 15, 1985-November 14, 1990.

National Science Foundation, NSF Grant ECS-8617860, "Stochastic Adaptive Estimation and Control," S.I. Marcus, Principal Investigator, September 1, 1987 - February 28, 1991.

II. SOLID STATE ELECTRONICS

Research Unit SSE89-1: GROWTH OF III-V COMPOUNDS BY MOLECULAR BEAM EPITAXY

Principal Investigator: Professor Ben G. Streetman (471-1754)

Graduate Students: T. Block, A. Campbell, A. Dodabalapur, T. Rogers, K. Sadra

A. SCIENTIFIC OBJECTIVES: Our objective is to study the growth of multilayer heterostructures in GaAs, AlGaAs, InGaAs, and related compounds by MBE, to improve the quality and variety of structures available and to apply these structures to electronic and optoelectronic devices. This work contributes to the other units in the UT-Austin JSEP compound semiconductor program by providing access to specialized MBE growth of multilayer heterostructures. We have developed extensive measurement capabilities which allow us to examine details of MBE growth at the monolayer and submonolayer scale, and also to use the resulting controlled growth for device development and studies of transport properties in semiconductor multilayers. Advanced structures grown in this work are used in the transport studies and device development research described in other MBE-related units in this program. Therefore, the major goals of this work are to develop new understanding of MBE growth, apply that understanding to the growth of high-quality multilayer heterostructures, characterize those structures, and work with related JSEP units to advance the science and art of devices based on such multilayers.

B. PROGRESS: We have examined MBE growth conditions required to obtain high-quality pseudomorphic $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}/\text{In}_y\text{Ga}_{1-y}\text{As}/\text{GaAs}$ ($y=0.15-0.2$) HEMT and quantum well structures [1,2]. Careful choices of As overpressure, growth temperatures and growth rates for the various layers are required to obtain HEMT structures with high mobilities. Rapid thermal annealing improves the low-field mobility and PL intensity of the structures. This improvement is attributed to improving crystalline quality of the InGaAs layer with annealing. The linewidth and energy of the PL transition between channel electrons and photoexcited holes are significantly influenced by the free-carrier concentration. Photoluminescence results indicate very little layer mixing across the interfaces after short-time annealing. We have also studied the photoluminescence (PL) properties of pseudomorphic modulation-doped $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}/\text{In}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaAs}$ quantum wells as a function of temperature. At 4.2K, hole localization influences the PL linewidth; however, at higher temperatures (77 K) the thermal energy of photoexcited holes is sufficiently large to obtain a reliable measure of sheet carrier density from the PL linewidth. Our results also suggest that information about the interface quality can be obtained from an analysis of the PL linewidth at 77 and 4.2 K. The spectra taken from several samples clearly show that the PL transition energy exhibits a free-carrier density dependence due to band-gap renormalization and electric field effects.

Recently [3] we have included electron beam electroluminescence (EBER) measurements, in collaboration with Charles Evans and Associates, to further correlate the studies of these modulation doped quantum wells (MDQWs). EBER spectra provide information about the transition energies of several quantum well related transitions as well as bulk transitions.

The temperature dependent PL linewidths of AlGaAs/InGaAs/GaAs MDQWs provide considerable information about such basic properties as carrier density and mobility. At low

temperatures (4.2 K), the PL linewidth is influenced by both the carrier density and material quality, whereas at higher temperatures (77 K) only the carrier density determines the PL linewidth. As a result, the linewidths of high quality MDQWs are strongly temperature dependent, whereas the linewidths of poor quality MDQWs are almost temperature independent in the range 4.2 - 77 K. The ratio of the 77 K to 4.2 K PL linewidths is a measure of the crystalline quality, and correlates extremely well with the observed 77 K mobilities of several samples. These nondestructive characterization techniques should be especially suitable for probing large area wafers for possible non-uniformities in the carrier density or mobility, and also to study the effects of processing steps on these parameters [3].

In our studies of the DX center, we have used ion implantation to modify the local environment of the defect in Si-doped $\text{Al}_{0.27}\text{Ga}_{0.73}\text{As}$ [4]. The variations in DX center properties with subsequent rapid thermal annealing processes were examined using deep level transient spectroscopy (DLTS). In the typical as-grown sample, two DX center peaks are found with the same activation energy of 0.46 ± 0.01 eV, but with widely different cross sections. The main DX center peak ME3, which appears at higher temperatures due to its smaller cross section, remains stable throughout the experiments. The second DX center peak ME2 has a much larger cross section, and appears at a lower temperature. The capture properties of this subsidiary DX center peak are markedly altered in the ion-implanted samples. Samples which were subject solely to the rapid thermal annealing processes have stable DX center trap signatures, indicating that arsenic loss during annealing does not significantly influence the DX center characteristics. We have proposed that regions of incomplete ordering and defect complexing in the AlGaAs film give rise to the various subsidiary DX center peaks observed.

Our studies of the DX center by DLTS have led us to investigate the use of the Williams-Watts or stretched exponential decay of the form $A(t) = \exp[-(t/\tau)^\beta]$ and variations of this form to analyze the capture and emission kinetics of the DX center [5]. We found that the time and temperature behavior of the DX center capture and emission characteristics can be reproduced with a thermally activated time constant τ and a linear dependence of β on temperature. Activation energies, lattice vibration frequencies, and models of implicit distributions of activation energies compare favorably to values previously found in the literature.

We have studied the use of low MBE growth temperatures to obtain high-resistivity materials appropriate for buffer layers [6]. GaAs and $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layers were grown by MBE at 250°C and incorporated as the gate insulator in MIS structures and examined using capacitance-voltage and current-voltage techniques. Samples which were not annealed, and samples annealed for 10 and 20 minutes under an arsenic ambient at 600°C were compared. MIS structures using material grown at low temperatures without annealing were found to be extremely leaky at room temperature due to a high defect concentration. For unannealed samples and samples annealed for 10 minutes, a deep level trap was found to be the source of free carriers in the low growth temperature layer. Capacitance-voltage profiling on both structures indicated the Fermi level was weakly pinned. For samples annealed for 20 minutes, however, no modulation of the device capacitance was possible, and the layer exhibited extremely high resistivity. This indicates that the Fermi level is pinned strongly in samples annealed for 20 minutes, possibly due to the precipitation and/or interfacial segregation of metallic As.

In our continuing study of details of MBE growth obtainable through imaging reflection high-energy electron diffraction (RHEED), we have examined intensity profiles along the specular streak of the RHEED pattern during MBE growth of GaAs [7]. These profiles show intensity peaks from diffuse scattering processes as well as the specular intensity peak. Intensity oscillations from the diffuse scattering peaks vary in phase with the intensity oscillation at the specular position, with the phase variation depending on the incident angle of the electron beam. Calculation of

major Kikuchi line escape angles near the [110] azimuth shows that the diffuse scattering peaks observed are at Kikuchi angles. At some incident angles, interference between Kikuchi and specular scattering was found to change the phase of the oscillation observed at the specular position, as reported by other workers. Interference from Kikuchi processes should be more easily avoided when observing along an azimuth a few degrees off of the [110] direction than when observing directly along the [110] direction. Oscillation phase versus escape angle measurements along an azimuth 7° off [110] show that the phase versus angle curve is somewhat less erratic than that measured directly along the [110] direction. We still find, however, that the oscillation phase observed at the specular position is shifted over much of the angular range, complicating the common interpretation in which RHEED oscillation maxima correspond to the smoothest growth surfaces.

Applications of multilayer heterostructures grown in our MBE work are described in other units of this report. Of particular interest is the quantum well resonant tunneling work described in SSE89-5. In our studies of tunneling we have measured the current-voltage characteristics of single-barrier AlAs/GaAs heterostructures over a wide temperature range to elucidate the mechanisms governing electron transport through these barriers [8]. Five barriers, ranging in thickness from 14.2 to 150 Å, were examined. The results clearly illustrate Γ -band, elastic-tunneling-dominated transport for the thinnest barrier (14.2 Å) devices and thermionic emission characteristics for the thickest barrier (150 Å) devices. However, devices with an intermediate barrier thickness exhibited tunneling-like currents larger than calculated low-temperature elastic tunneling currents. This effect is apparently due to inelastic tunneling from the GaAs Γ band through the AlAs X-point barrier. The analysis of AlAs/GaAs single-barrier structures of varying barrier thickness clearly demonstrates the importance of accounting for current transport involving the AlAs X band. Elastic tunneling through a 1.05 eV AlAs Γ -point barrier accounts for the measured currents of only the very thin 14.2 Å AlAs barrier devices. Conduction in thick 150 Å AlAs barrier devices is well described near room temperature by thermionic emission over a 0.2 eV barrier corresponding to the calculated $\Gamma_{\text{GaAs}}\text{-X}_{\text{AlAs}}$ conduction-band offset. Devices with a barrier thickness between the two extremes exhibited tunneling-like currents larger than calculated elastic tunneling currents at low temperatures, apparently because of inelastic tunneling from the GaAs Γ band through the AlAs X-point barrier. Inelastic $\Gamma_{\text{GaAs}}\text{-X}_{\text{AlAs}}$ tunneling becomes increasingly more important for wider barriers as shown by the larger discrepancy between the measured currents and calculated elastic tunneling currents for thicker AlAs barriers. These results indicate that, except for ultrathin tunneling barriers (≈ 14.2 Å), the indirect AlAs X band must be considered when analyzing, designing, or optimizing devices employing AlAs/GaAs tunnel structures.

C. FOLLOW-UP STATEMENT: We will continue to study the details of MBE growth using imaging RHEED and the quality of layers in the InGaAlAs system using both electrical and optical measurements. Devices employing multilayer heterostructures will be studied in collaboration with other units in this program. During the upcoming year we intend to develop capabilities for growing antimonides in our system. The resulting narrow-bandgap materials will be of particular interest in various optoelectronic applications.

D. REFERENCES:

1. A. Dodabalapur, V.P. Kesan, T.R. Block, D.P. Neikirk, and B.G. Streetman, "Optical and Electrical Characterization of Pseudomorphic AlGaAs/InGaAs/GaAs Modulation-Doped Structures Processed by RTA," J. Vac. Science and Techn., **B7**, pp. 380-383 (1989).
 2. A. Dodabalapur, V.P. Kesan, D.R. Hinson, D.P. Neikirk, and B.G. Streetman, "Photoluminescence Studies of Pseudomorphic Modulation-doped AlGaAs/InGaAs/GaAs Quantum Wells," Applied Physics Letters, **54**, pp. 1675-1677 (1989).
 3. A. Dodabalapur, V.P. Kesan, D.P. Neikirk, B.G. Streetman, M.H. Herman, and I.O. Ward, "Photoluminescence and Electoreflectance Studies of Modulation-Doped Pseudomorphic AlGaAs/InGaAs/GaAs Quantum Wells," to appear in J. Electron. Mater.
 4. A.C. Campbell, A. Dodabalapur, G.E. Crook, and B.G. Streetman, "Study of the DX Center Fine Structure in Ion-Implanted $\text{Al}_{0.27}\text{Ga}_{0.73}\text{As}$ Processed by Rapid Thermal Annealing," Applied Physics Letters, **54**, pp. 727-729 (1989).
 5. A.C. Campbell and B.G. Streetman, "Application of the Williams-Watts Decay Law to DX Center Capture and Emission Kinetics," Applied Physics Letters, **54**, pp. 445-447 (1989).
 6. A.C. Campbell, G.E. Crook, T.J. Rogers, and B.G. Streetman, "Investigation of Low Growth Temperature AlGaAs and GaAs Using MIS Diagnostic Structures," to appear in J. Vac. Science and Techn. **B** (March, 1990).
 7. G.E. Crook, K.G. Eyink, A.C. Campbell, D. Hinson, and B.G. Streetman, "Effects of Kikuchi Scattering on RHEED Intensities During MBE GaAs Growth," J. Vac. Science and Techn., **A7**, pp. 2549-2553 (1989).
 8. C.S. Kyono, V.P. Kesan, D.P. Neikirk, C.M. Maziar, and B.G. Streetman, "Dependence of Apparent Barrier Height on Barrier Thickness for Perpendicular Transport in AlAs/GaAs Single Barrier Structures Grown by MBE," Applied Physics Letters, **54**, pp. 549-551 (1989).
- I. LIST OF PUBLICATIONS (*JSEP supported in whole or in part)
- * A. Dodabalapur and B.G. Streetman, "Rapid Thermal Annealing of Dual Si and P Implants in InP," J. Electronic Materials, **18**, pp. 65-68 (1989).
 - * A.C. Campbell and B.G. Streetman, "Application of the Williams-Watts Decay Law to DX Center Capture and Emission Kinetics," Appl. Phys. Lett., **54**, pp. 445-447 (1989).
 - * C.S. Kyono, V.P. Kesan, D.P. Neikirk, C.M. Maziar, and B.G. Streetman, "Dependence of Apparent Barrier Height on Barrier Thickness for Perpendicular Transport in AlAs/GaAs Single Barrier Structures Grown by MBE," Appl. Phys. Letters, **54**, pp. 549-551 (1989).

- * A.C. Campbell, A. Dodabalapur, G.E. Crook, and B.G. Streetman, "Study of the DX Center Fine Structure in Ion-Implanted $\text{Al}_{0.27}\text{Ga}_{0.73}\text{As}$ Processed by Rapid Thermal Annealing," Applied Physics Letters, **54**, pp. 727-729 (1989).
- * T.J. Mattord, V.P. Kesan, D.P. Neikirk, and B.G. Streetman, "A Single-Filament Effusion Cell With Reduced Thermal Gradient for Molecular Beam Epitaxy," J. Vac. Science and Techn. **B7**, pp. 214-216 (1989).
- * A. Dodabalapur, V.P. Kesan, T.R. Block, D.P. Neikirk, and B.G. Streetman, "Optical and Electrical Characterization of Pseudomorphic AlGaAs/InGaAs/GaAs Modulation-Doped Structures Processed by RTA," J. Vac. Science and Techn. **B7**, pp. 380-383 (1989).
- * A. Dodabalapur, V.P. Kesan, D.R. Hinson, D.P. Neikirk, and B.G. Streetman, "Photoluminescence Studies of Pseudomorphic Modulation-doped AlGaAs/InGaAs/GaAs Quantum Wells," Applied Physics Letters, **54**, pp. 1675-1677 (1989).
- * G.E. Crook, K.G. Eyink, A.C. Campbell, D. Hinson, and B.G. Streetman, "Effects of Kikuchi Scattering on RHEED Intensities During MBE GaAs Growth," J. Vac. Science and Techn. **A7**, pp. 2549-2553 (1989).
- * A.C. Campbell, V.P. Kesan, T.R. Block, G.E. Crook, D.P. Neikirk, and B.G. Streetman, "Influence of MBE Growth Temperature on GaAs/AlAs Resonant Tunneling Structures," J. Electronic Materials, **18**, pp. 585-588 (1989).
- * K. Sadra, C.M. Maziar, and B.G. Streetman, "The Role of the Split-off Band in Electron-Hole Energy Exchange Dynamics in Selected III-V Semiconductors," J. Applied Physics, **66**, pp. 2020-2026 (1989).
- * K. Sadra, C.M. Maziar, B.G. Streetman, and D.S. Tang, "Effects of Multiband Electron-Hole Scattering and Hole Wavefunction Symmetry on Minority-Electron Transport in GaAs," to appear in J. Applied Physics.
- * A. Dodabalapur, V.P. Kesan, D.P. Neikirk, and B.G. Streetman, "Photoluminescence and Electoreflectance Studies of Modulation-Doped Pseudomorphic AlGaAs/InGaAs/GaAs Quantum Wells," submitted to J. Electron. Mater.
- * A.C. Campbell, G.E. Crook, T.J. Rogers, and B.G. Streetman, "Investigation of Low Growth Temperature AlGaAs and GaAs Using MIS Diagnostic Structures," to appear in J. Vac. Science and Techn. B (March, 1990).

II. LIST OF CONFERENCE PROCEEDINGS (*JSEP supported in whole or in part)

- * C.M. Maziar, K.Sadra, and B.G. Streetman, "Monte Carlo Simulation of Minority-Carrier Transport in III-V Semiconductors," pp. 508-516 in Proc. of Fourth International Conf. on Supercomputing, Santa Clara (May, 1989).

- * B.G. Streetman and A. Dodabalapur, "Implantation in InP: The Role of Stoichiometric Imbalances," to appear in Ion Implantation for Elemental and Compound Semiconductors, R. Jones and S.J. Pearton, eds. Electrochemical Society Proceedings (1989).
- * K. Sadra, C.M. Maziar, and B.G. Streetman, "Electron-Hole Scattering and Minority-Electron Transport in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$, InAs, and InP: The Role of the Split-Off Band," SPIE Conf. Proceedings, vol. 1144: InP and Related Materials for Advanced Electronic and Optical Devices, Norman OK (1989).
- * M.H. Herman, A. Dodabalapur, I.O. Ward, and B.G. Streetman, "Characterization of Undoped Pseudomorphic InGaAs/GaAs Quantum Wells by Electron Beam Electroluminescence (EBER) and Photoluminescence (PL)," to appear in MRS. Symposia Proc. on Layers Structures, L.J. Schowalter, et al. editors (1989).

III. LIST OF PRESENTATIONS (*JSEP supported in whole or in part)

Presentations during 1989 at the EMC, MBE Workshop, InP Conference, Conference on Supercomputing, Electrochemical Society and MRS meetings are summarized in the publications listed above.

IV. LIST OF THESES AND DISSERTATIONS (*JSEP supported in whole or in part)

- * G. E. Crook, Ph.D., May 1989, "Use of Specular Streak Intensity Profiling in Reflection High-Energy Electron Diffraction Studies of Molecular Beam Epitaxy."
- * A.C. Campbell, Ph.D., August 1989, "Influence of the Silicon Donor (DX Center) and Growth Temperatures on GaAs/AlGaAs Heterostructures Grown by Molecular Beam Epitaxy."
- * T.J. Rogers, M.S., "Molecular Beam Epitaxial Growth of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ on InP Substrates."

V. CONTRACTS AND GRANTS

Army Research Office, Contract DAAL03-88-K-0060, "Quantitative RHEED Studies of MBE Growth of III-V Compounds," Prof. Ben Streetman, Principal Investigator.

Texas Advanced Technology Program (TATP), "Heterostructure Tunneling Devices for Ultra-High Speed Device Applications," Professors Ben G. Streetman and Dean P. Neikirk, Co-Principal Investigators.

Research Unit SSE89-2: EPITAXIAL GROWTH AT III-V SEMICONDUCTOR SURFACES

Principal Investigator: Professor J.L. Erskine (471-1464)

Graduate Students: D.C. Anacker and Craig Ballentine

A. SCIENTIFIC OBJECTIVES: This research unit explores physical phenomena associated with epitaxial growth. The work is focused on the GaAs(100) surface, because of its technological importance, and emphasizes the use of a variety of electron spectroscopic techniques to probe the structure, dynamics and electronic properties associated with the surface and thin epitaxial layers. The scientific objectives of the work are to:

- extend fundamental studies of compound formation and Schottky barrier properties of III-V semiconductors to include the (100) "growth template" surface
- elucidate factors that underlie the stability of reconstructed surfaces and interfaces
- identify factors that govern the initial stage of epitaxial film nucleation, including surface roughness, steps, reconstructions; and, study their affects on device-related properties such as the Schottky barrier height
- explore the relationship between interface lattice strain and epitaxial layer properties such as electronic structure and vibrational structure (phonons)
- develop new methods for probing transport dynamics and electrical characteristics of ultra-thin films based on photoelectron emission by two-photon femtosecond pulse excitation.

OVERVIEW: Refinements in semiconductor synthesis techniques, particularly molecular beam epitaxy, are leading to new classes of microelectronics devices based on the novel properties of III-V semiconductor multilayers and superlattices. New device structures, such as quantum wells and tunneling barriers, require precise atomic-level control of the epitaxial growth process to achieve uniform and well-defined electrical characteristics. Requirements to precisely control crystal perfection, interface definition, composition and impurity concentrations in epitaxial films are leading to a need for improved fundamental understanding of atomic-level phenomena that govern substrate structure, film nucleation and growth, and related device parameters.

This work unit is focussed on selected issues associated with epitaxial growth at GaAs(100) surfaces. The primary objective of the work is to probe fundamental issues related to the origin and stability of reconstructed surfaces, and to explore the relationship between structure, composition, vibrational dynamics and electronic properties of thin epitaxial layers. Because of the relative ease of preparing GaAs(110) surfaces by cleaving a bulk crystal, most of the fundamental work on Schottky barrier formation and interface chemistry in III-V semiconductors has been done on this cleavage plane. Our work will help extend this type of knowledge to

include the (100) surface of GaAs. Fundamental understanding of the atomic-level phenomena that stabilize surface geometry is a prerequisite for controlling epitaxial growth and the structure of grown materials as well as their electrical properties. This premise is the basis for our effort and serves as a guide for selecting systems for study and for defining general objectives of the planned experiments. Our research emphasizes the use of spectroscopic probes (based on electrons) to study atomic-level properties of surfaces. Specific atomic-level properties that are accessible to accurate spectroscopic characterization include surface phonons [1-3] (by inelastic electron scattering), bulk and surface electronic states (by angle resolved photoelectron emission spectroscopy) [4-5] and surface crystal structure (elastic electron scattering) [6-7]. Quasi-elastic electron scattering [8-11] can be used to probe low energy (meV) excitations such as plasma losses and other scattering channels that are effective in ultra-thin films on semiconductor surfaces.

B. PROGRESS: This research unit initiates a new program. The present reporting period, therefore, covers a transition between two work units having significantly different objectives. The previous work unit has been highly successful and has achieved important new results in the field of thin film magnetism [12-17]. This effort has continued under the present JSEP funding cycle in order to permit the two students supported by JSEP (Jose Araya-Pochet and Craig Ballentine) to complete their Ph.D. work. Both have now finished their work, and transfer support to continue this project is being sought from the National Science Foundation and from the Office of Naval Research. Progress on this project is described in detail in recent publications [12-15], invited talks, and in the two Ph.D. dissertations [16,17]. A new student (D.C. Anacker) has replaced Jose Araya-Pochet, and is now working on the joint project with Professor M.C. Downer described in the section of our proposal entitled: "Femtosecond Angle Resolved Photoemission Spectroscopy". As described in the proposal, we have set up a compact ultra-high vacuum system equipped with low energy electron diffraction and Auger electron spectroscopy capability for characterizing the single crystal samples used in our preliminary experiments. We have developed a time-of-flight electron energy analyzer that provides adequate energy resolution (100 meV) and efficient detection characteristics for initial experiments. The time-of-flight spectrometer has now been interfaced to a transient digitizer and software has been written to capture time-of-flight data in a single shot mode. Initial experiments have revealed an unexpected new phenomena involving the emission of hot electrons (50-100 eV) from Ag(100) surfaces upon radiation by 100 femtosecond pulses at fluences of 10^{12} w/cm². This effect is quite unexpected (at the intensity levels used in the experiment) and we are conducting experiments designed to elucidate the mechanism responsible for this novel effect.

The third area in which we summarize progress represents the intended primary thrust of our work unit as new instrumentation becomes fully commissioned, and as the previous program on magnetic thin films is transferred to students not supported by JSEP. The two instruments which will be used to carry out spectroscopic studies of GaAs(100) surfaces and epitaxial growth of metal and semiconductor films on GaAs(100) have been commissioned during the past one year reporting period and are now yielding scientific results. One instrument is the (NSF funded) University of Texas synchrotron radiation beamline at Brookhaven National Laboratory. This facility will be used to study the electronic properties of GaAs(100) and epitaxial layers as outlined in our proposal. The second instrument is a new surface phonon spectrometer (DoD funded) which will be used to study surface dynamics of semiconductor surfaces. A second year student (Joan Yater) will be transferred to JSEP support after Craig Ballentine leaves. Joan has already begun to set up the molecular beam epitaxy cells, and other capabilities needed to begin our proposed studies of the surface dynamics of semiconductor surfaces and thin films.

C. FOLLOW-UP STATEMENT: Although our JSEP supported efforts on ultra-thin magnetic films has been highly productive, we remain committed to seeking transfer support for this program and phasing it out in 1989. We have agreed to help support a primary JSEP thrust area involving III-V semiconductor surfaces. The new emphasis will be to probe the structure, stability, and growth mechanisms associated with III-V semiconductor surfaces and superlattices. Our new instrumentation, including a highly sensitive surface phonon spectrometer and our new beamline and endstation at NSLS, provide the necessary tools to carry out leading edge work in this area.

D. REFERENCES:

1. M. Rocca, H. Ibach, S. Lehwald, and T.S. Rahman, *Topics in Current Physics*, **41** 245 (1986).
2. J.L. Erskine, *CRC Critical Reviews in Solid State and Materials Science*, **13** 311-379 (1987).
3. H. Ibach and D.L. Mills, Electron Energy Loss Spectroscopy and Surface Vibrations, Academic Press: New York (1982).
4. E.W. Plummer and W. Eberhardt, *Adv. Chem. Phys.* **49**, 533 (1982).
5. B. Feuerbacher and R.F. Willis, *J. Phys. C.-Solid State Physics* **9**, 169 (1976).
6. J.B. Pendry, Low Energy Electron Diffraction, Academic Press: New York (1974).
7. M.A. Van Hove, W.H. Weinberg, C.-M. Chan, Low Energy Electron Diffraction, Springer-Verlag: Berlin (1986).
8. B.N.J. Persson and J.E. Demuth, *Phys. Rev.* **B31**, 1856 (1985).
9. B.N.J. Persson and J.E. Demuth, *Phys. Rev.* **B30**, 5986 (1984).
10. B.N.J. Persson and J.E. Demuth, *Solid State Commun.* **53**, 1573 (1984).
11. L.H. Dubois, G.P. Schwartz, R.E. Camley, and D.L. Mills, *Phys. Rev.* **B29**, 3208 (1984).
12. J. Araya-Pochet, C.A. Ballentine, T.-Y. Hsieh, and J.L. Erskine, *Proc. Solvay Conf. on Surface Science*, (ed.) F.W. deWette, Springer-Verlag (1988).
13. J. Araya-Pochet, C.A. Ballentine, and J.L. Erskine, *Phys. Rev.* **B38**, 7846 (1988) (*Rapid Communication*).
14. J.L. Erskine, C.A. Ballentine, J. Araya-Pochet, and R.L. Fink, *Proc. Materials Res. Soc.* **143**, 45 (1989).
15. C.A. Ballentine, R.L. Fink, Jose Araya-Pochet, and J.L. Erskine, *Applied Physics A* (in press).

16. Jose Araya-Pochet, Ph.D. Dissertation, University of Texas at Austin (1988).
17. C.A. Ballentine, Ph.D. Dissertation, University of Texas at Austin (1989).

I. LIST OF PUBLICATIONS (*JSEP supported in whole or in part)

S. Varma, M. Onellion, Y. Kime, P.A. Dowben, and J.L. Erskine, "Solid State Effects on the Hg 5d Branching Ratio", *J. Phys. C* (in press).

- * B.-S. Fang, C.A. Ballentine, and J.L. Erskine, "Bulk Plasmon Enhanced Photoemission from Nb(100)", *Phys. Rev. B* **38**, 4299 (1988).

- * J. Araya-Pochet, C.A. Ballentine, and J.L. Erskine, "Thickness and Temperature Dependent Spin Anisotropy of Ultra-thin Epitaxial Fe Films on Ag(100)", *Phys. Rev. B* **38**, 7846 (1988) (*Rapid Communication*).

- * B.-S. Fang, C.A. Ballentine, and J.L. Erskine, "Hydrogen Adsorption at Nb(100): Photoemission Evidence of Two-state Exchange Involving Subsurface States", *Surface Sci. Lett.* **204**, L713 (1988).

M.F. Onellion, P.A. Dowben, and J.L. Erskine, "The Relationship Between the Crystallographic Order and Electronic Structure of Mercury Thin Films", *Phys. Lett. A* **130**, 171 (1988).

- * J. Araya-Pochet, C.A. Ballentine, T.-Y. Hsieh, and J.L. Erskine, "Magneto-optic Kerr Effect Studies of Two-dimensional Magnetism", *Proc. Solvay Conf. on Surface Sci.*, (ed.) F.W. deWette, Springer Verlag (1988).

D. Anacker and J.L. Erskine, "Design of NSLS Undulator Beamline U5 for Spin-polarized Photoemission Spectroscopy", *Nucl. Inst. Methods*, **A226** 336 (1988).

Eue-Jin Jeong and J.L. Erskine, "Multichannel Detection High Resolution Electron Energy Loss Spectrometer", *Rev. Sci. Instrum.* **60**, 3139 (1989).

A. Sellidj and J.L. Erskine, "Electron Energy Loss Spectroscopy Studies of Nitrogen Adsorption on W(100)", *Surface Science* (in press).

A. Sellidj and J.L. Erskine, "A Tandem Four-element Lens System for Inelastic Electron Scattering Studies", *Rev. Sci. Instrum.* (in press).

- * J.L. Erskine, C.A. Ballentine, J. Araya-Pochet, and R.L. Fink, "Synchrotron Radiation Studies of Magnetic Materials", *Proc. Materials Res. Soc.* **143**, 45 (1989).

D.C. Anacker, W. Hale, and J.L. Erskine, "An Algorithm for Computer Simulation of Undulators and Wigglers", *Nucl. Instrum. and Methods*, (in press).

- * C.A. Ballentine, R.L. Fink, Jose Araya-Pochet, and J.L. Erskine, "Exploring Magnetic Properties of Ultra-thin Epitaxial Magnetic Structures Using Magneto-optical Techniques", *Applied Physics A*, (in press).
- * C.A. Ballentine, R.L. Fink, Jose Araya-Pochet, and J.L. Erskine, "Magnetic Phase Transition in a Two-dimensional System: p(1x1) Ni on Cu(111)", *Phys. Rev. B* (in press).
- P.A. Dowben, M.F. Onellion, S. Varma, Y.K. Kime, and J.L. Erskine, "The Influence of Crystallographic Order Upon the Electronic Structure of Thin Mercury Overlayers", *J. Vac. Sci. Technol. A*, 2070 (1989).

II. LIST OF CONFERENCE PROCEEDINGS

- Conference "Surface Vibrations on Clean and Hydrogen Covered Nb(110) Surfaces", Y. Li, A.D. Kulkarni, J.L. Erskine, and F.W. deWette, March Meeting of the American Physical Society, St. Louis, Missouri, March 20-24, 1989, *Bull. Am. Phys. Soc.* **34** (3) [1989].
- Conference "Multichannel Detection High Resolution Electron Energy Loss Spectrometer", Eue-Jin Jeong and J.L. Erskine, March Meeting of the American Physical Society, St. Louis, Missouri, March 20-24, 1989, *Bull. Am. Phys. Soc.* **34** (3) [1989].
- Conference "UPS Study of Nitrogen Adsorption on W(100) at 135 K", A. Sellidj and J.L. Erskine, March Meeting of the American Physical Society, St. Louis, Missouri, March 20-24, 1989, *Bull. Am. Phys. Soc.* **34** (3) [1989].
- Conference "Magnetic Properties of Ultra-thin Epitaxial Films of V on Ag(100)", R.L. Fink, J.A. Araya-Pochet, C.A. Ballentine, and J.L. Erskine, March Meeting of the American Physical Society, St. Louis, Missouri, March 20-24, 1989, *Bull. Am. Phys. Soc.* **34** (3) [1989].
- Conference "Magneto-optical Studies of Transition Metal Epitaxial Ultra Thin Films", J.A. Araya-Pochet, C.A. Ballentine, R.L. Fink, and J.L. Erskine, March Meeting of the American Physical Society, St. Louis, Missouri, March 20-24, 1989, *Bull. Am. Phys. Soc.* **34** (3) [1989].
- Conference "Temperature and Thickness Dependence of Magnetization for Ultra-thin Ni Films on Cu(111)", C.A. Ballentine, J.A. Araya-Pochet, R.L. Fink, and J.L. Erskine, March Meeting of the American Physical Society, St. Louis, Missouri, March 20-24, 1989, *Bull. Am. Phys. Soc.* **34** (3) [1989].
- Seminar "Thin Film Magnetic Phase Transitions", J.L. Erskine, Department of Physics, Montana State University, Bozeman, Montana, June 22, 1989.
- Conference "Magneto-optic Studies of Ultra-thin Film and Surface Magnetism", C.A. Ballentine and J.L. Erskine, Forty-Ninth Annual Conference on Physical Electronics, Seattle, Washington, June 26-28, 1989.

- Invited "Magneto-optical Studies of Thin Film Magnetism", J.L. Erskine, Workshop on Monolayer Magnetism, Berkeley Springs, West Virginia, August 14-17, 1989.
- Invited "Dead Layers in Thin Film Magnetism: p(1x1) Ni on Ag(100) and Ag(111)", J. Araya-Pochet, C.A. Ballentine, and J.L. Erskine, International Workshop on the Magnetic Properties of Low Dimensional Systems, Universidad Autonoma de San Luis Potosi, San Luis Potosi, S.L.P. Mexico, May 22-16, 1989.
- Seminar "Magneto-optical Studies of Thin Film Magnetism", J.L. Erskine, Sandia National Laboratories, Sandia, New Mexico, March 13, 1989.
- Seminar "Inelastic Electron Scattering Studies of Surface Phonons", J.L. Erskine, Department of Physics, Indiana University, Bloomington, Indiana, April 7, 1989.

III. LIST OF THESES AND DISSERTATIONS

C.A. Ballentine, Ph.D., October 1989, "Magneto-optical Studies of Fe, Ni, V and Ph Ultra-thin Films on Ag(100), Ag(111), Cu(100) and Cu(111) Single Crystal Substrates", (supported by JSEP).

IV. CONTRACTS AND GRANTS

The Robert A. Welch Foundation Welch F-1015, "Electron Scattering Studies of H/Nb(100)", Dr. J.L. Erskine, Principal Investigator, 1987-1990.

National Science Foundation DMR-8702848, "Experimental Studies of Intrinsic Surface Electronic and Magnetic Properties", Dr. J.L. Erskine, Principal Investigator, 1987-1989.

National Science Foundation DMR-8906935, "Fundamental Studies of Magnetic Materials", Dr. J.L. Erskine, Principal Investigator, 1989-1992.

Air Force Office of Scientific Research 89-NC-090, "High Resolution Electron Energy Loss Studies", Dr. J.L. Erskine, Principal Investigator, 1989-1992.

Joint Services Electronic Program, "Epitaxial Growth at III-V Semiconductor Surfaces", Dr. J.L. Erskine, Principal Investigator, 1988-1991.

Research Unit SSE89-3: CHARGE TRANSPORT IN NOVEL DEVICE STRUCTURES AND MATERIALS

Principal Investigator: Professor Christine M. Maziar (471-3674)

Graduate Students: Paul C. Colestock, Carl Kyono and Kayvan Sadra

A. SCIENTIFIC OBJECTIVES: The focus of this research unit is the study of charge transport in semiconductors on ultra-small spatial and temporal scales. We believe that it is essential for a successful modern materials and device research effort that strong experimental, modeling and simulation programs be coordinated for the study of transport phenomena. The understanding and exploitation of promising materials and device concepts is most fully realized when accurate models are available to device researchers and materials scientists. Such models are most successfully developed when a simulation effort is tightly coupled with experimental work. Just such coordination is a key feature of the ongoing research in this unit. Our studies are proceeding along three lines, all focused on carrier transport and all making use of the Monte Carlo simulation technique, MBE grown films (Streetman and Neikirk), and the expertise of the femtosecond spectroscopy group (Downer). At the suggestion of last fall's JSEP review panel, we have also initiated a study which will investigate the use of noise measurements to characterize transport through heterointerface structures.

Minority Carrier Transport: Although the importance of minority carrier transport in device physics is widely recognized, surprisingly little detailed experimental or theoretical work has been devoted to the study of minority carrier transport in III-V semiconductors. Theoretical calculations by Walukiewicz et al. [1] suggest that minority electron mobilities in GaAs are as little as one third of those of majority electron mobilities (depending on concentration and compensation). Unfortunately, experimental work which supports or challenges Walukiewicz's calculations is sparse and inconclusive. Perhaps of greater significance is the absence of an extensive body of work (both experimental and theoretical) describing high field minority carrier transport in III-V's.

Short minority-carrier lifetimes and ohmic heating effects make measurements of minority-carrier transport parameters difficult to perform in III-V's and necessitate the use of indirect [2-4] or ultra-fast optical techniques. The development of minority carrier transport models suitable for device analysis and design has been hampered as a result. Aside from technological considerations, an added incentive for careful investigation of minority-carrier behavior is the observation of a variety of intriguing phenomena. It has been found, for example, that minority electrons in GaAs quantum wells exhibit negative differential mobility at low temperatures and under low electric fields. [5]. Particularly interesting is the apparent absence of negative differential mobility in measurements made on $p\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$. Electric fields as high as 7.5 kV/cm produce velocities in the range of $\sim 2.6 \times 10^7$ cm/s [6].

In our work we have developed and are continuing to develop an advanced Monte Carlo simulation tool capable of simulating both electron and hole transport as well as minority carrier electron transport. During the remainder of this research program we will enhance the simulator by including additional physical sophistication (e.g. dynamic screening). The simulator will also be

used to simulate transport measurements to be made on these III-V materials in an effort to isolate the source of discrepancy between the currently available experimental results and state of the art simulation results.

QWITT Simulation Support: The transport simulation group is very pleased to collaborate with D. Neirkirk's Heterostructure Device Development efforts (SSE89-5). The most significant challenge, or opportunity, is the development of a detailed understanding of the role the quantum-well injector plays in the transport features of the transit region. Early simulations of HBT structures illustrated the strong influence that the initial carrier energy distribution has on carrier transport on short spatial and temporal scales. Currently, we lack detailed knowledge of the features of the carrier energy distribution at the injecting plane of the quantum well. This does not prevent us, however, from using semiclassical tools to describe carrier transport in the transit time region. The Monte Carlo technique is an excellent choice for a simulation tool to investigate the nature of the impact that strongly non-Maxwellian distribution functions will have on transport in this region.

The nature of the transport through heterostructure barriers composed of materials which differ in the symmetry of the lowest conduction band states (a so-called "anisogap" barrier, see Figure 1) has attracted theoretical and experimental efforts by a number of groups [7-8]. Because the QWITT may be realized in a version with high aluminum fraction barriers a careful study of transport through anisogap barriers is called for. The study of such transport requires an experimental activity coupled with theory and simulator development.

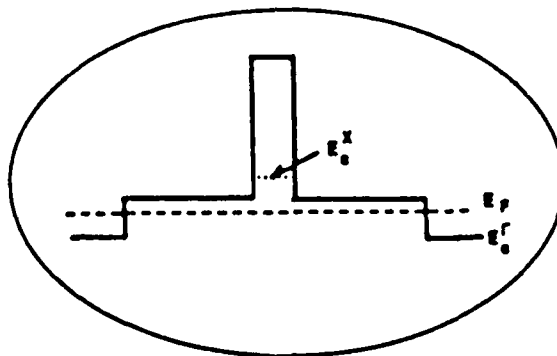


Figure 1.

The outcome of this work will be a better understanding of transport through "anisogap" barriers and tunneling structures and the development of noise measurement techniques as a means of characterizing such transport. This work will also assist in the optimization of the drift region of the QWITT.

B. **PROGRESS:** Since funding of this unit in April a significant number of milestones have been reached, particularly in the development of the minority carrier simulator. Our progress in the area of QWITT transport simulation support and barrier transport characterization has been somewhat slower, primarily because of the time lag involved in finding the appropriate student to work on this project. With the addition of Paul Colestock to the group (PhD student, previously with Texas

Instruments and The University of South Florida), we have gained tremendous momentum in our efforts to put together noise measurement capabilities for barrier transport characterization. The status of the minority carrier transport studies and the QWITT simulation support are further outlined below.

Minority Carrier Simulation: As described in the Scientific Objectives section, experimental work indicates that minority electrons in $p\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ may not experience negative differential mobility and that saturated velocities for minority electrons may be significantly higher than saturated velocities for majority carrier electrons. This absence of negative differential mobility suggests an energy-relaxing mechanism which acts to maintain the carriers in the low-mass Γ -valley. Such a mechanism may be attractive for exploitation in a device context. Monte Carlo simulations by Osman [9], however, did not replicate the experimental result. The scattering mechanisms used in that simulator neglected both light holes and interband processes. Moreover, that simulator neglected overlap integrals between initial and final wavefunctions of the holes. Although the simulator demonstrated enhanced relaxation of electrons through intraband scattering with heavy holes, their calculated relaxation was much smaller than that suggested by experiment. In an effort to explain this discrepancy we improved the theoretical model to see if the gap between theory and experiment could be bridged. A number of improvements which we made, including multi-band electron-hole scattering, inclusion of the split-off band and a more complete description of hole overlap functions should be of interest to those working on simulators to describe ultrafast relaxation processes in semiconductors.

The following new capabilities have been added to our Monte Carlo simulator:

- Includes multiband electron-hole scattering (for example $\Gamma\Gamma^h$ - an electron in the gamma band scatters with a hole with initial state in the light hole band but final state in the heavy hole band...see Figure 2)
 - We learned that the multi-band processes may make a significant contribution to electron energy loss rates to holes. This is evident because of the generally larger change in energy possible with an interband transition.
 - We learned the hole overlap factors could not be neglected. Failure to include overlap results in a substantial overestimate of the energy loss rate by electrons to holes.
- Extended the simulator to studies of InP and InGaAs and included electron-hole scattering processes involving the split-off band (Figures 3 and 4).
 - We learned that processes involving the split-off band were much more important for InP than for InGaAs. We were able to relate these observations to hole overlap factors and the relative magnitudes of the Γ -L separation and split-off energy.

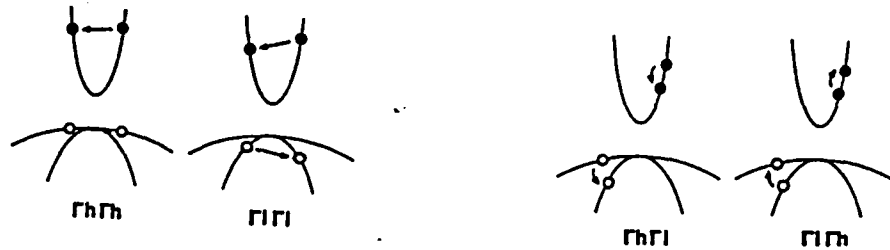
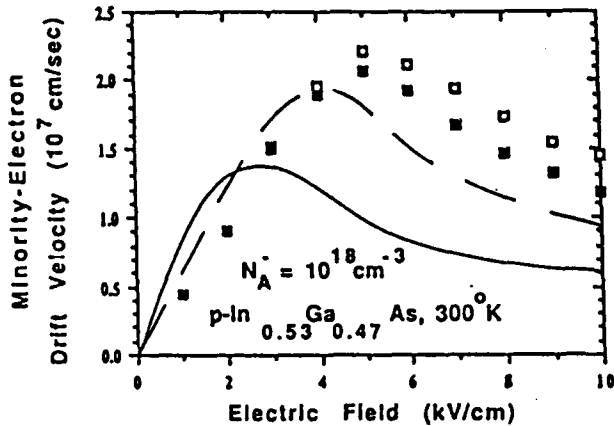
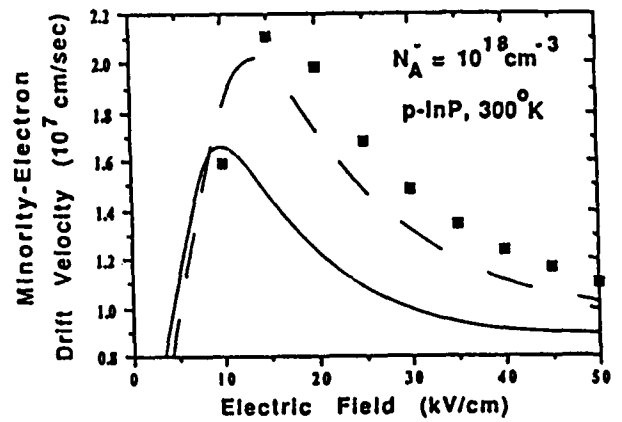


Figure 2.



Velocity-field characteristics of minority electrons in $p\text{-InP}$, GaAs , As with (filled squares) and without (empty squares) hole overlap factors in $\Gamma_h\Gamma_h$ and $\Gamma_l\Gamma_l$ processes. Solid and dashed lines are majority-electron results for equivalent donor concentration with the polar phonon interaction statically screened and unscreened, respectively.

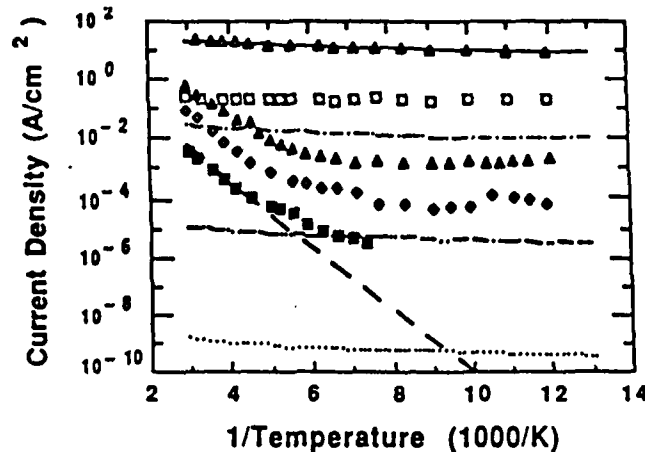
Figure 3



Velocity-field characteristics of minority electrons in $p\text{-InP}$ (filled squares). Solid and dashed lines are majority-electron results for equivalent donor concentration with the polar phonon interaction statically screened and unscreened, respectively.

Figure 4

QWITT support: The roles of barrier width and multiple conduction bands were investigated. We used single barrier AlAs/GaAs structures as the test vehicle for studying the interplay between multiple conduction bands and barrier width on carrier transport. This choice was motivated by the simplicity of the structure as well as its importance to RTDs. Although much early RTD work utilized direct band-gap barriers of Al(x)Ga(1-x)As ($x < 0.4$), researchers have turned to AlAs barriers because of the larger $\Gamma_{\text{GaAs}}-\Gamma_{\text{AlAs}}$ conduction band offsets and absence of alloy disorder in the barrier. Figure 5 illustrates the results of measurements made on single-barrier structures grown by UT-Austin's MBE group (Streetman and Neikirk).



Current density as a function of inverse temperature for AlAs/GaAs single-barrier structures of varying barrier thickness (14.2, 31.1, 50.9, 73.6, and 150 Å) at a bias voltage of 5 mV. The figure shows a comparison of experimental measurements (Δ , 14.2 Å; \square , 31.1 Å; \blacktriangle , 50.9 Å; \diamond , 73.6 Å; and \blacksquare , 150 Å) with calculated elastic tunneling current densities [(—) 14.2 Å, (—) 31.1 Å, (—) 50.9 Å, and (···) 73.6 Å] and thermionic emission current densities [(---) assumes $q\Phi_b = 0.2$ eV and $A = 3 \times 10^{-4}$ A/cm² K²].

Figure 5.

The analysis the data indicates that the X-band of the AlAs barrier plays an increasingly important role as barrier thicknesses increase. Elastic tunneling through a 1.05 eV AlAs Γ -point barrier accounts for the measured currents of only the very thin 14.2 Å point barrier accounts for the measured currents of only the very thin 14.2 Å AlAs barriers. Conduction in thick 150 Å AlAs barrier is well described near room temperature by thermionic emission over a 0.2 eV barrier corresponding to the $\Gamma_{\text{GaAs}}-\text{X}_{\text{AlAs}}$ conduction band offset. Devices with a barrier thickness between the two extremes exhibited tunneling-like currents larger than the calculated elastic tunneling current, apparently because of inelastic tunneling through the X-barrier in the AlAs. These results indicate that, within the exception of extremely thin barriers, the AlAs X-band must be considered when analyzing, designing or optimizing devices employing AlAs/GaAs tunnel structures.

C. FOLLOW-UP STATEMENT: This work is continuing. Work during the coming year will focus on the application of the advanced Monte Carlo models described above in model device contexts. Preliminary experimental design has been completed for the evaluation of noise measurements as a tool for probing barrier transport. Preliminary experimental work followed by application of Monte Carlo tools for experiment evaluation and analysis will be aggressively pursued. Evaluation of potential advantages of "iso-gap" tunneling structures for RTD application (in contrast to the "aniso-gap" GaAs/AlAs barriers) is well underway.

D. REFERENCES:

1. W. Walukiewicz, J. Lagowski, L. Jastrzebski and H. C. Gatos, "Minority-Carrier Mobility in p-Type GaAs," J. Appl. Phys., 50(7), 5040, (1979).
2. M. I. Nathan, W. P. Dumke, K. Wrenner, S. Tiwari, S. L. Wright, and K. A. Jenkins, Appl. Phys. Lett., 52, 664, (1988).
3. R. K. Ahrenkiel, D. J. Dunlavy, D. Greenberg, J. Schlupmann, H. C. Hamaker and H. F. MacMillan, "Electron Mobility in p-GaAs by Time of Flight," Appl. Phys. Lett., 51, 776, (1987).
4. R. J. Nelson, *Gallium Arsenide and Related Compounds*, 1978 (Institute of Physics, Bristol and London, 1979), p. 256.
5. R. A. Hopfel, J. Shah, P. A. Wolff, and A. C. Gossard, Phys. Rev. Let. 56, 2736, (1986).
6. J. Degani, R. F. Leheny, R. E. Nahory and J. P. Heritage, "Velocity Field Characteristics of Minority Carriers (Electrons) in $p\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$," J. Appl. Phys. Lett., 39(7), 569, (1981).
7. A. R. Bonnefoi, D. H. Chow, T. C. McGill, R. D. Burnham, and F. A. Ponce, "Current Transport Mechanisms in GaAs/AlAs Tunnel Structures Grown by Metal-Organic Chemical Vapor Deposition," J. Vac. Sci. Tech. B., 4(4), 988, (1986).
8. C. S. Kyono, V. P. Kesan, D. P. Neikirk, C. M. Maziar and B. G. Streetman, "Dependence of Apparent Barrier Height on Barrier Thickness for Perpendicular Transport in AlAs/GaAs Single-Barrier Structures Grown by Molecular Beam Epitaxy," *Appl. Phys. Lett.*, 54(6), 549 (1989).
9. M. A. Osman and H. L. Grubin, "Monte Carlo Investigation of Minority Electron Transport in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$," *Appl. Phys. Lett.*, 51(22), 1812, 1987.

I. List of Publications

K. Sadra, C. M. Maziar and B. G. Streetman, "The role of the split-off band in electron-hole energy exchange dynamics in selected III-V semiconductors," *J. Appl. Phys.*, vol. 66, no. 5, pp. 2020-2026, September 1, 1989.

K. Sadra, C. M. Maziar, B. G. Streetman and D. S. Tang, "Effects of Multiband Electron-Hole Scattering and Hole Wavefunction Symmetry on Minority Electron Transport in GaAs," accepted for publication in *J. Appl. Phys.*

C. S. Kyono, V. P. Kesan, D. P. Neikirk, C. M. Maziar and B. G. Streetman, "Dependence of Apparent Barrier Height on Barrier Thickness for Perpendicular Transport in AlAs/GaAs Single-Barrier Structures Grown by Molecular Beam Epitaxy," *Appl. Phys. Lett.*, vol. 54, no. 6, pp. 549-551, February 6, 1989.

II. Conference Proceedings

K. Sadra, C. M. Maziar and B. G. Streetman, "Electron-hole scattering and minority-electron transport in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$, InAs , and InP : the role of the split-off band," *The Proceedings of the First International Conference on Indium Phosphide and Related Materials for Advanced Electronic and Optical Devices*, March 1989, Norman, Oklahoma.

C. M. Maziar, K. Sadra and B. G. Streetman, "Monte Carlo Simulation of Minority Carrier Transport in III-V Semiconductors (invited paper)," *Proceedings of the Fourth International Conference on Supercomputing*, April 30- May 5, 1989, Santa Clara, California, pp. 508-516.

V. Grants and Contracts

"Modeling and Simulation of Charge Transport in InP Lattice Matched Materials and Device Structures," The National Science Foundation, \$70,000, 6/88-12/90.

"Analysis and Simulation of Ultra-Small Structures," (with Al Tasch) Texas Higher Education Coordinating Board, \$143,839, 6/88-8/90.

"Charge Transport in Enhanced Velocity Structures," Texas Higher Education Coordinating Board, \$77,626, 6/88-8/90.

Research Unit SSE89-4: FEMTOSECOND PROCESSES IN III-V SEMICONDUCTORS

Principal Investigator: Professor M. C. Downer (471-6054)

Graduate Students: Glenn Focht and David H. Reitze

A. SCIENTIFIC OBJECTIVES: We seek insight into the physics of ultrafast processes in technologically important solids, with emphasis on III-V semiconductors, using the techniques of femtosecond laser spectroscopy.

B. PROGRESS: During the first year of this triennium, progress has centered on completing several projects begun in the previous triennium, and preparing extensions of these projects which focus specifically on III-V materials.

In the previous two years we reported our invention of an efficient femtosecond source in the ultraviolet based on intracavity frequency doubling [1] and our development of a quantitative theory of this new class of ultraviolet passively mode-locked source [2]. JSEP-supported graduate student Glenn Focht has now demonstrated two applications of this unamplified source to ultrafast semiconductor physics which make use of its unique capability to provide synchronized ultraviolet and red femtosecond pulse trains of comparable power and pulse duration. Completion of these applications is the final stage of his Ph.D. work.

In the first application, a red pump pulse optically excites carriers in a semiconducting sample, and a time-delayed, attenuated ultraviolet pulse probes the time-dependent reflectivity and/or transmission of the sample. The essential point of this application is that our ultraviolet photon energy (4.0 eV.) falls on the edge of the E_2 absorption / reflectivity peak in most Column IV, III-V, and II-VI materials [3]. It is therefore extremely sensitive to small shifts in the E_2 peak induced by optically injected carriers (electronic band renormalization) [4] or by lattice heating (thermal band renormalization) [5]. Because of its short wavelength, the probe is also *insensitive* to interband saturation and the Drude contribution of the electron-hole plasma. Since electronic carriers and lattice heat are introduced into the sample on different time scales, the experiment can and does distinguish the relative importance of electronic and thermal contributions to renormalization of the bands responsible for the E_2 peak. Our main experimental result from Column IV samples (carbon (crystalline graphite), silicon, germanium) is that renormalization is delayed by several hundred femtoseconds following excitation. This result shows that the initial hot carriers on a cold lattice induce only a weak band renormalization, while the cold carriers and hot lattice which follow within a few hundred femtoseconds induce a strong band renormalization. Theoretical calculations [4,6] of electronic band renormalization have so far assumed cold ($T = 0^\circ\text{K}$) carrier populations, and have examined only the shift of the band edge (E_0 point). Our results should therefore stimulate theoretical work on the influence of hot carriers and the renormalization of higher energy bands. The results with crystalline graphite comprise part of a manuscript in preparation for Physical Review B [7]. Other results will be published separately after further analysis. Extensions of these experiments to III-V materials and heterostructures are planned. For example, preparation of an AlGaAs sample with band gap slightly greater than the pump photon energy (2.0 eV) will allow initial injection of cold carriers, and suppress lattice heating. We can therefore determine whether the observed renormalization is caused by the cold carrier

distribution or lattice heating. Experiments on quasi-two-dimensional samples should also be possible.

In the second application, an ultraviolet pump pulse optically excites extremely hot carriers in a semiconducting sample, and a time-delayed, attenuated red pulse probes the time-dependent reflectivity and/or transmission of the sample. Since the red probe is primarily sensitive to interband saturation and the Drude contribution, it probes the density and energy distribution of the photoexcited carriers. As expected, the first results reveal qualitatively different dynamics for carriers induced by red and ultraviolet pump pulses. However, these results are recent, and further analysis is needed to reach a clear interpretation. Monte Carlo simulation (Research Unit SSE89-3) is expected to play a role in this analysis.

Last year we reported initial experiments investigating the interaction of intense, tightly focused femtosecond pulses (peak intensity as high as 10^{16} W/cm²) with both dense gaseous and solid targets. This rapidly emerging field is driven by the motivation to develop new short pulse or coherent X-ray sources [8,9], and by the wealth of new physics when unprecedented optical energy densities interact with dense matter on a femtosecond time scale. This year we have completed and expanded upon the initial experiments, and developed new lines of investigation, as outlined in the following paragraphs. Our recent contributions have resulted in several invited presentations at international meetings (see below).

Our measurements and analysis of nonlinear absorption processes in silicon under intense femtosecond excitation conditions, performed by JSEP-supported graduate student David Reitze and described in detail in last year's annual report, have been accepted for publication [10]. Although originally only a brief paper for Applied Physics Letters was intended, further analysis of the results justified submission of a full-length paper to the Journal of the Optical Society of America B, currently in press. The understanding gained in this work relates pivotally to several other experiments in our laboratory. Initial carrier energy distributions injected by two-photon absorption, the dominant nonlinearity, closely resemble those injected by an ultraviolet pump in the experiment described above. Therefore the relaxation dynamics should be similar. Furthermore, the initial hot carrier distribution created by two-photon absorption should be a prominent feature of femtosecond photoemission spectra (see below) at high excitation when these experiments are extended to semiconductors. Finally the precise knowledge of nonlinear absorption coefficients which has been gained gives us an accurate figure for carrier density reached under laser annealing conditions, and supports the hypothesis that electronic dissociation induced by a densely populated anti-bonding conduction band [11,12] plays a dominant role in the structural disordering of silicon on a femtosecond time scale.

Reitze has performed new experiments [7,13] on the intense excitation and melting of carbon, one row above silicon in Column IV of the periodic table, as the final stage of his Ph.D work. The choice of carbon (in both crystalline graphite and diamond forms) for these experiments was motivated by several factors: 1. Carbon is an important target material in prototype X-ray laser experiments. 2. Since graphite is the most refractory material known to mankind, no material exists as a crucible for studying the molten phase; thus it can be only be studied transiently following short pulse laser excitation. 3. Previous experiments [14-16] with long laser pulses generated a controversy over the material properties of the molten phase, particularly whether it is a metal or insulator, which have been addressed and clarified by our femtosecond experiments. 4. Diamond is structurally identical to silicon and the III-V materials. 5. Graphite is a naturally-occurring quasi-two-dimensional material. Experiments were performed both below [7] and above [13] the threshold for melting, and show sharply contrasting optical responses. Experiments below threshold [7] trace the generation, relaxation, and recombination of electronic carriers, as well as band renormalization effects, through time-resolved reflectivity and transmission experiments on a femtosecond time scale. Experiments above threshold [13]

have used time-resolved reflectivity over a range of wavelengths to determine the dynamics of the melting process. Strong evidence for a two-stage melting dynamic, exhibiting first metallic, then insulating properties, has been obtained, and is consistent at long time delays with earlier experiments with much longer pulses [16]. These dynamics are believed to be closely related to the structural anisotropy of the starting material. Analogous experiments on diamond are expected to yield a one-stage melting dynamic similar to that observed in silicon [17]. Planned extensions to III-V materials involve the use of ternary target materials (AlGaAs) with band gap near the pump photon energy in order to minimize lattice heating, and the preparation of target samples with absorbing (e.g. low gap, GaAs) layers buried at controlled distances within non-absorbing (e.g. high gap, AlAs) matrices, in order to investigate melt front propagation.

Two other experiments involving intense femtosecond excitation of dense gaseous or solid targets, now supported primarily by other agencies (NSF and ONR), have also progressed significantly over the past year. Last year we reported experiments on strong field ionization of dense gases using intense, tightly focused femtosecond pulses (peak intensity 10^{16} W/cm²) from a novel amplifier developed under JSEP sponsorship in our laboratory [18]. A major motivation behind such experiments is the ability to deliver intense, *collisionless* excitation to gases at up to 100 atm., creating cold, dense, highly stripped plasmas: the principal combination of conditions required for X-ray recombination lasers [9]. Our dye amplifier, though producing lower intensity than some excimer amplified systems, has the unique advantage of suppressing amplified spontaneous emission (ASE) background with common fast saturable absorber dyes, thus eliminating pre-ionization in high intensity experiments, and opening the doorway to femtosecond time-resolved experiments not possible with many of the more powerful systems. Last year we reported single pulse ionization experiments which revealed a strong spectral blue shift in the pulse transmitted through the strong field ionization region [18,19]. Detailed analysis of this blue shift [19] is a powerful diagnostic of strong field ionization in dense gases. Manuscripts presenting greatly extended experiments and analysis are in preparation. New femtosecond time-resolved pump-probe experiments have also been performed. These experiments reveal a blue shift in the probe during ionization, and a small red shift at later time delays. This red shift is believed to be related to the subsequent dynamics, possibly recombination, of the cold, dense, highly stripped plasma created by intense femtosecond excitation. These results were presented by the P.I. at an invited paper at the Optical Society of America Topical Meeting on High Energy Density Physics with Subpicosecond Lasers [20]. Current experiments are investigating the time-resolved response in more detail, and developing alternate diagnostics of the evolving plasma density.

High intensity excitation effects are also being investigated at metal surfaces through femtosecond angle-resolved photoemission (ONR sponsorship), in collaboration with J.L. Erskine (Research Unit SSE89-2), as described in the previous annual report. The major finding is the photoemission of anomalously high energy (100 eV) electrons from Ag (111), centered sharply around the normal photoemission direction, upon excitation below the melting threshold with 90 fs. pulses at 2 eV or 4 eV. The motivation behind studying this excitation regime is that intense, ultrashort laser pulses interacting with metal surfaces can produce ultrashort x-ray pulses useful as probes or calibrating sources [8], and can heat the metal greatly before any expansion occurs, permitting the study of hot material or even plasma at solid density [9]. Our study of photoemission under similar excitation conditions provides a new, independent avenue for probing the unique physics of this regime. Intensity-, wavelength-, polarization-, angle- and time-dependence of this photoemission signal are currently being characterized in order to elucidate the underlying photoemission mechanism.

In collaboration with Itoh and Neikirk (Research Unit EM89-1), a picosecond mode-locked Nd:YAG laser, funded by the Defense University Research Instrumentation Program (DURIP)

through AFOSR, has been purchased and is operational. It is dedicated to picosecond optoelectronic probing of high speed integrated circuit structures, with initial emphasis on small-scale transmission line structures containing precisely fabricated discontinuities, chosen for their importance in high speed monolithic digital electronics. Prototype transmission line structures have been fabricated, and construction of the experimental detection system for optoelectronic sampling is underway. These experiments use the direct, temporally compressed output of the Nd:YAG laser. Simultaneously, most major components for the near infrared femtosecond dye laser (see previous annual report), to be synchronously pumped by the Nd:YAG laser, are now in hand, and its construction can begin shortly.

C. FOLLOW-UP STATEMENT: This report has described the completion or continuing progress of several projects begun in the previous triennium. Emphasis will now be placed on extensions of some of these projects to III-V materials or processes relevant to III-V technology. Specific foci for the coming year will be: 1) extension of femtosecond UV reflectivity experiments to III-V materials; 2) extension of femtosecond melting experiments to III-V structures; 3) performance of optoelectronic sampling measurements on prototype transmission line structures containing discontinuities.

D. REFERENCES:

1. G. Focht and M.C. Downer, IEEE J. Quant. Electron. 24, 431 (1988).
2. T.R. Zhang, G. Focht, and M.C. Downer, IEEE J. Quant. Electron. 24, 1877 (1988).
3. R.R.L. Zucca and Y.R. Shen, Phys. Rev. B1, 2668 (1970).
4. K.F. Berggren and B.E. Sernelius, Phys. Rev. B24, 1971 (1981).
5. J.M. Moison, F. Barthe, and P. Bensoussan, Phys. Rev. B27, 3611 (1983).
6. S. DasSarma and M. Stopa, Phys. Rev. B36, 9595 (1987).
7. K. Seibert, H. Kurz, A.M. Malvezzi, D.H. Reitze, and M.C. Downer, "Femtosecond Carrier Dynamics in Graphite" (in preparation).
8. O.R. Wood II, W.T. Silfvast, H.W.K. Tom, W.H. Knox, R.L. Fork, C.H. Brito-Cruz, M.C. Downer, and P.J. Maloney, Appl. Phys. Lett. 53, 654 (1988).
9. N.H. Burnett and P.B. Corkum, J. Opt. Soc. Am. B (May 1989).
10. D.H. Reitze, T.R. Zhang, W.M. Wood, and M.C. Downer, J. Opt. Soc. Am. B (in press).
11. R. Biswas and V. Ambegaokar, Phys. Rev. B26, 1980 (1982).
12. H.W.K. Tom and C.H. Brito-Cruz, Phys. Rev. Lett. 60, 1438 (1988).
13. D.H. Reitze, X. Wang, H. Ahn, and M.C. Downer, Phys. Rev. B Rapid Communications (in press).

14. T. Venkatesan, D.C. Jacobson, J.M. Gibson, B.S. Elman, G. Braunstein, M.S. Dresselhaus, and G. Dresselhaus, Phys. Rev. Lett. 53, 360 (1984).
15. J. Heremans, C.H. Olk, G.L. Eesley, J. Steinbeck, and G. Dresselhaus, Phys. Rev. Lett. 60, 452 (1988).
16. A.M. Malvezzi, N. Bloembergen, and C.Y. Huang, Phys. Rev. Lett. 57, 146 (1986).
17. M.C. Downer, R.L. Fork, and C.V. Shank, J. Opt. Soc. Am. B 2, 595 (1985).
18. W.M. Wood, G. Focht, and M.C. Downer, Opt. Lett. 13, 984 (1988).
19. M.C. Downer, G. Focht, D.H. Reitze, W.M. Wood, and T.R. Zhang, Ultrafast Phenomena VI (Springer Verlag 1988), p. 128.
20. M.C. Downer, W.M. Wood, W. Banyai, and J. Trisnadi, in Technical Digest of Optical Society of America Topical Meeting on High Energy Density Physics with Subpicosecond Lasers (Optical Society of America 1989).
21. H.M. Milchberg, R.R. Freeman, S.C. Davey, and R.M. More, Phys. Rev. Lett. 61, 2364 (1988).

I. LIST OF PUBLICATIONS

D.H. Reitze, T.R. Zhang, W.M. Wood, and M.C. Downer, "Two-photon spectroscopy of silicon using femtosecond pulses at above gap frequencies," J. Opt. Soc. Am. B (in press).

D.H. Reitze, X. Wang, H. Ahn, and M.C. Downer, "Femtosecond laser melting of graphite," Phys. Rev. B, Rapid Communications (in press).

G.W. Burdick, M.C. Downer, and D.K. Sardar, "A new contribution to spin-forbidden rare earth optical transition intensities: analysis of all trivalent lanthanides," J. Chem. Phys. 91, 1511 (1989).

II. LIST OF CONFERENCE PROCEEDINGS

D.H. Reitze, T.R. Zhang, W.M. Wood, and M.C. Downer, "Semiconductor Absorption Nonlinearity and Optical Damage in the Femtosecond Regime," J. Electrochem. Soc. 135, 387 (1988).

W.M. Wood, G. Focht, T.R. Zhang, D.H. Reitze, and M.C. Downer, "Blue Shifting of Intense Femtosecond Pulses During Strong Field Ionization: Direct Measurement of the Keldysh Quiver Energy," Conference on Lasers and Electro-Optics Technical Digest Series 11, 36 (1989).

D.H. Reitze, X. Wang, H. Ahn, and M.C. Downer, "Femtosecond laser melting of graphite," Quantum Electronics and Laser Science Postdeadline Digest (Optical Society of America 1989) paper PD17-1.

III. LIST OF PRESENTATIONS

[Invited] M.C. Downer, G. Focht, T.R. Zhang, "Extending femtosecond spectroscopy to the ultraviolet," Society of Photo-Instrumentation Engineers (SPIE) Conference on Deep Blue and Ultraviolet Lasers: Technology and Applications, Los Angeles, CA (January 19, 1989).

[Invited] M.C. Downer, "Blue shifting of femtosecond light pulses during strong field ionization," Walter Schottky Conference on Ultrafast Physical Phenomena, Aachen, West Germany (May 10, 1989). Also given at Max Planck Institute for Quantum Optics, Munich, West Germany (May 24, 1989).

[Invited] M.C. Downer, W.M. Wood, W. Banyai, and J. Trisnadi, "Spectral shifting of intense femtosecond light pulses during strong field ionization and subsequent plasma dynamics," Optical Society of America Topical Meeting on High Energy Density Physics with Subpicosecond Lasers, Snowbird, Utah (September 12, 1989).

[Invited] M.C. Downer, D.H. Reitze, "Femtosecond phase transitions in silicon and graphite," U.S.-Japan Exchange Seminar on Excited State Dynamics in the Condensed Phase, Honolulu, Hawaii (November 6, 1989).

D.H. Reitze, T.R. Zhang, and M.C. Downer, "Measurement of two-photon absorption coefficient of silicon at above gap frequencies by femtosecond spectroscopy," March meeting of the American Physical Society, St. Louis, Mo. (March 23, 1989).

IV. LIST OF THESES AND DISSERTATIONS

NONE

V. CONTRACTS AND GRANTS

National Science Foundation (Presidential Young Investigator Award), "Femtosecond Processes in Condensed Matter" (DMR 8858388), M.C. Downer, P.I.

Office of Naval Research (Young Investigator Award), "Femtosecond Angle-Resolved Photoemission Spectroscopy of Electronic Materials" (Contract N00014-88-K-0663), M.C. Downer, P.I.

Office of Naval Research, "Femtosecond Angle-Resolved Photoemission Spectroscopy of Metals and Semiconductors" (Contract N00014-88-K-0754), M.C. Downer, P.I.

Air Force Office of Scientific Research (Defense University Research Instrumentation Program), "Picosecond Laser system for High Speed Characterization of Monolithic Devices" (Grant AFOSR-89-0209), M.C. Downer, D.P. Neikirk, and T. Itoh, P.I.'s.

(Page 7, Res. Unit SSE89-4. "Femtosecond Processes in III-V Semiconductors")

Robert A. Welch Foundation, "Femtosecond Photoemission and Photodesorption Spectroscopy of Excited States at Surfaces," (Grant F-1038), M.C. Downer, P.I.

Research Unit SSE89-5: HETEROSTRUCTURE DEVICE DEVELOPMENT

Principal Investigator: Professor D. P. Neikirk (471-4669)

Graduate Students: V. Kesan, V. Reddy

A. SCIENTIFIC OBJECTIVES: The use of such techniques as molecular beam epitaxy has allowed the fabrication of devices in which tunneling is the dominant transport mechanism. In this unit a new transit time device which uses resonant tunneling through a quantum well is investigated. Depending on the bias level, this device may permit injection of carriers into the drift region at more favorable phase angles (hence higher efficiencies) than other transit time devices. The device promises low noise performance and should be capable of operating at high millimeter wave frequencies with higher output power than other transit time devices or pure quantum well oscillators. Since the device uses quantum well injection and transit time effects, it is called a QWITT diode. The issues which must be addressed to allow successful QWITT fabrication and operation center on (i) quantum well design for injected pulse optimization, (ii) the choice of optimum drift region characteristics, and (iii) the design of microwave and millimeter wave resonator structures with sufficient Q to allow QWITT oscillation over a narrow bandwidth. Each of these issues requires that certain tasks be accomplished. These include: i) AlAs/GaAs QWITT diode growth and dc characterization; ii) investigation of InGaAs/InAlAs quantum well structures for enhanced peak-to-valley ratios and current densities; and iii) through interactions with the Electromagnetics Unit EM89-1 "Millimeter Wave Active Guided Wave Structures" resonators will be constructed to allow measurements on QWITT oscillators designed and grown by our research group.

B. PROGRESS:**QWITT Diode Fabrication and DC Characterization**

During the late 1988 and 1989 time period we have completed preliminary fabrication and testing of our QWITT diodes. The heterolayers used in this study were grown in a Varian GEN II MBE system on n^+ ($3\text{-}5 \times 10^{18} \text{ cm}^{-3}$ Si-doped) (100) GaAs substrates. A schematic diagram of the device structures used in this study is shown in Fig. 1. Three QWITT device structures, A, B, and C, consisting of identical quantum well regions but with three different n^- ($5 \times 10^{16} \text{ cm}^{-3}$ Si-doped) GaAs drift region lengths of 500Å, 1000Å, and 2000Å respectively, were examined [1]. A maximum depletion region length of 2000Å was chosen, since that corresponds to the optimum length of the drift region for 10 GHz operation based on the small signal model for the QWITT diode [2]. The quantum well regions consisted of a 50Å GaAs layer sandwiched between two AlAs layers 17Å thick. The AlAs barrier layers were kept thin to increase the current density through the device, and to also promote $\Gamma(\text{GaAs})\text{-}\Gamma(\text{AlAs})$ tunneling [3]. A 250Å thick GaAs spacer region consisting of a 100Å n -type ($1 \times 10^{17} \text{ cm}^{-3}$ Si-doped) layer, followed by a 100Å, n -type ($1 \times 10^{16} \text{ cm}^{-3}$ Si-doped) layer, with a 50Å, unintentionally doped p -type ($\sim 1 \times 10^{14} \text{ cm}^{-3}$) layer,

was used on the cathode side of the devices (Fig. 1). In addition, a baseline resonant tunneling diode structure, D, with the same quantum well layers and with the same 250Å GaAs spacer layer on either side of the device was grown. Device mesas were defined using conventional photolithography and wet etching techniques. Device diameters were typically 4-8 μm , corresponding to a device area of $1.25\text{-}5 \times 10^{-7} \text{ cm}^2$. Continuous and pulsed (50% duty cycle) dc current-voltage characteristics at room temperature were measured.

For QWITT devices containing a uniformly doped depletion region, our self-consistent large signal model [4] indicates that the electric field in this region is of the order of 100 kV/cm. For GaAs, electric fields around 3-10 kV/cm are sufficient to have carrier velocities around 10^7 cm/sec . Hence, we have also tested a new QWITT structure which introduces a doping spike at the beginning of the drift region, much like that in a lo-hi-lo IMPATT structure [5]. This reduces the electric field in the GaAs drift region, while the entire drift region remains fully depleted. This should result in a reduction in the dc bias across the device and hence improve the dc-to-rf conversion efficiency. Since the entire drift region is still depleted the voltage swing between peak and valley should remain the same, and thus the rf output power will not be reduced compared to the uniformly doped drift region device. Fig. 2 shows a schematic of the device structures, E through H, examined in this study. Device E corresponds to the limiting case when the doping concentration in the spike equals the background doping of $5 \times 10^{16} \text{ cm}^{-3}$ in the drift region. Devices F through H contain a 100Å GaAs doping spike of varying Si doping concentration from $8 \times 10^{16} \text{ cm}^{-3}$ to $5 \times 10^{17} \text{ cm}^{-3}$ at the beginning of the drift region followed by a 1800Å n-type GaAs layer ($5 \times 10^{16} \text{ cm}^{-3}$ Si-doped). Note that the total thickness of the GaAs layers following the quantum well region on the anode side is constant at 2000Å from devices A through H (Figs. 1 & 2). All the device structures E through H have identical quantum well regions and cathode spacer layers.

Table I shows the room temperature dc I-V characteristics obtained from devices A through D. The QWITT bias direction corresponds to electron injection from the top contact. The I-V characteristics in either bias direction for sample D are quite symmetric with a typical peak-to-valley current ratio of 2-3:1 and a peak current density of around 20 kA/cm^2 . Due to the asymmetric structure of the QWITT diode (structures A through C), the dc I-V characteristics for the two bias directions are very different. In any negative resistance diode the voltage and current difference between peak and valley, ΔV_{pv} and ΔI_{pv} , must be as large as possible to increase the device output power; in a low frequency model (i.e., frequencies below $\omega_0 = |\sigma|/\epsilon$) maximum output power should be proportional to $\Delta V_{pv} \cdot \Delta I_{pv}$. For the QWITT diode, ΔV_{pv} is increased through the use of a drift region, but ΔI_{pv} should remain virtually the same as in the intrinsic quantum well. This should result in an increase in the total output power that can be obtained from the QWITT diode compared to a bare resonant tunneling diode. For the QWITT bias mode (forward bias, substrate positive), as the length of the drift region is increased from 500Å to 2000Å, the voltage corresponding to the current peak, V_p , increases from 2.4V to 5.1V, and the voltage difference between peak and valley currents, ΔV_{pv} , also increases from 0.3V to 1.1V (Fig. 3 and Table I). We can see that while the variation in peak-to-valley current differences, ΔJ_{pv} , and peak current density, J_p , for the three devices A, B, and C, is quite small, large differences in ΔV_{pv} are observed (Table I). Devices A and D have very similar voltage swings, ΔV_{pv} , since the length of the depletion region in both these structures is almost the same. The increase in ΔV_{pv} obtained

through a proper choice of the depletion region length also results in a corresponding increase in the specific negative resistance ($\Delta V_{pv}/\Delta J_{pv}$) of the device. This suggests that the best oscillator performance in terms of output power would be obtained from device C. For this quantum well structure, when the depletion region length is increased much beyond 2000Å, the small signal and large signal analyses [2, 4] for the QWITT diode show that the voltage swing between peak and valley, ΔV_{pv} , actually decreases due to the increased positive resistance in the device arising from both the space charge resistance and the undepleted portion of the drift region. This would then result in a degradation in the rf performance of the diode. For each device structure, when electrons are injected from the substrate to the top (reverse bias, substrate negative) ΔV_{pv} is smaller as compared to when electrons are injected from the top to the substrate (forward bias). This is because in reverse bias the n⁻ GaAs drift region is under accumulation, and can add only positive series resistance to the device, thus reducing ΔV_{pv} , as opposed to the QWITT mode, where this region actually contributes to the negative resistance of the device.

A systematic study of the variations in peak voltage and peak current, due to both processing conditions and reproducibility of the device structure by MBE, was undertaken. We found 10% variation in peak voltage from process-induced changes, arising primarily from variations in the quality of the ohmic contacts, caused by small changes in the AuGe/Ni metallization scheme. InGaAs-based ohmic contacts [6] should significantly improve the ohmic contact reproducibility. Changes in nominally the same device structure from one MBE growth run to another were found to be within the 10% change in voltage due to processing variations. We have also found 20% variation in the peak current density arising primarily due to inaccuracy in the estimate of the device area.

In devices E through H a doping spike was introduced at the beginning of the drift region to reduce the electric field and thus decrease the dc bias, but yet fully deplete the entire drift region. Table II shows the room temperature dc I-V characteristics obtained from devices E through H. By changing the doping concentration in the spike from $5 \times 10^{16} \text{ cm}^{-3}$ to $5 \times 10^{17} \text{ cm}^{-3}$ the peak voltage is reduced from 3.5V in device E to 0.64V in device H. However, the voltage swing, ΔV_{pv} , is also reduced from 1.1V to 0.34V, suggesting that the lightly doped GaAs drift region is not fully depleted. By reducing the spike doping concentration to $1 \times 10^{17} \text{ cm}^{-3}$ in device G the voltage swing, ΔV_{pv} , improves to 0.64V but this value is still lower than that seen in the uniformly doped device E. A further reduction in the spike doping concentration to $8 \times 10^{16} \text{ cm}^{-3}$ in device F causes ΔV_{pv} to recover to 1.2V. Note that the peak voltage in device F is about 30% lower compared to device E, but the voltage swing, ΔV_{pv} , and the current swing, ΔJ_{pv} , for the two devices are similar. This suggests that the oscillator output power obtained from devices E and F should be the same, with device F having higher efficiency due to the lower dc bias obtained through the introduction of a doping spike. The room temperature dc I-V curves for devices E and F are shown in Fig. 4. As seen before in devices A through C, in the opposite bias direction when the drift region is under accumulation the increased series resistance in the device causes a reduction in the voltage swing, ΔV_{pv} .

In order to calculate the specific negative resistance for these devices, the intrinsic injection conductance ($\sigma = \partial J / \partial E$) of the quantum well is determined from the experimental dc I-V characteristics by accounting for the voltage drops in the GaAs spacer regions using a drift/diffusion formalism [4]. For the samples, A, B, C, and D the injection conductance is found to

be -0.24, -0.28, -0.20, and -0.15 mho/cm respectively. This value for σ is then used to predict the specific negative resistance for the three devices [2] by assuming a constant carrier velocity in the drift region of 2×10^7 cm/sec (Table. III). We can see from Table III that the measured specific negative resistance, $(\Delta V/\Delta J)$, obtained from the dc characteristics of the diode compares well with the predicted values [2].

The microwave properties of our QWITT diodes have also been measured. Table III summarizes these results. Best performance was a peak output power of 1 mW, corresponding to an output power density of $3.5\text{--}5$ kW/cm², in the frequency range of 5-8 GHz has been obtained from a planar QWITT oscillator. Millimeter wave oscillations at 28-31 GHz in a waveguide circuit with an output power of 30 μ W have been obtained. In addition, good qualitative agreement between dc and rf characteristics of QWITT devices and theoretical predictions based on small signal and large signal analyses has been obtained. In addition, device F with a 8×10^{16} doping spike produced 1 mW of rf output power at an efficiency of 5%. For a complete discussion of the measured rf properties of these QWITT diodes, see EM89-1 "Millimeter Wave Active Guided Wave Structures."

In conclusion, both dc and microwave characteristics of different QWITT devices with both uniformly doped drift regions and with drift regions containing a doping spike have been determined. As shown in EM89-1 "Millimeter Wave Active Guided Wave Structures" when characterizing QWITT diode oscillators at frequencies below the characteristic frequency, $|\sigma|/2\pi\epsilon$ (this frequency is typically around 40 GHz for $|\sigma|=0.3$ mho/cm), the dc characteristics do prove to be a good measure of rf oscillator performance. Under these circumstances the best microwave oscillator performance is obtained by choosing a device structure that maximizes the $\Delta V_{pv} \cdot \Delta I_{pv}$ product. This is consistent with the small signal analysis for the QWITT diode [2] where we found that the specific negative resistance for a QWITT diode is essentially constant from dc up to frequencies around $|\sigma|/2\pi\epsilon$.

C. FOLLOW-UP STATEMENT: Even with the improvements predicted due to inclusion of a transit time region, the specific negative resistance at high frequencies for QWITT diodes is small. Thus, the maximum oscillation frequency of quantum well diode structures will probably be limited by parasitic device elements, such as specific contact resistance and impedance matching constraints. Clearly, the specific contact resistance in these devices must be minimized; InGaAs-based contacts with a specific negative resistance of around 10^{-7} $\Omega\text{-cm}^2$ may be necessary for high frequency oscillation.

Optimization of quantum well characteristics for the QWITT diode presents several non-trivial problems. The well must produce suitable injected carrier pulses, at dc bias levels consistent with required drift region fields. The models already developed by our group clearly indicates that current density is of paramount importance for high power operation. Recent work on InGaAs quantum wells with InAlAs barriers has shown significant improvements in peak-to-valley current ratios while maintaining high peak current densities. This is thought to be due to the much larger Γ -to-X conduction band edge discontinuities in this system, as compared to the GaAs/AlAs system. We have begun work on the growth of high quality pseudomorphic InGaAs quantum wells (see Unit SSE89-1, "Growth of III-V Compounds by Molecular Beam Epitaxy"), as well as devices lattice matched to a InP substrate. We have obtained preliminary results for the lattice matched system, but further work on the growth of these layers will be required over the next year

D. REFERENCES

1. V.P. Kesan, A. Mortazawi, D.R. Miller, T. Itoh, B.G. Streetman, and D.P. Neikirk, "Microwave frequency operation of quantum-well injection transit time (QWITT) diode," Elect. Lett., vol. 24, no. 24, pp. 1473-1474, 24 Nov. 1988.
2. V.P. Kesan, D.P. Neikirk, P.A. Blakey, and B.G. Streetman, and T.D. Linton, "Influence of transit time effects on the optimum design and maximum oscillation frequency of quantum well oscillators," IEEE Trans. on Elect. Dev., vol. ED-35, no. 4, pp. 405-413, April 1988.
3. C.S. Kyono, V.P. Kesan, D.P. Neikirk, C.M. Maziar, and B.G. Streetman, "Dependence of apparent barrier height on barrier thickness for perpendicular transport in AlAs/GaAs single barrier structures grown by MBE," Appl. Phys. Lett., vol. 54, no. 6, pp. 549-551, 6 Feb. 1989.
4. D.R. Miller, V.P. Kesan, R.L. Rogers, C.M. Maziar, and D.P. Neikirk, "Time dependent simulation of the Quantum Well Injection Transit Time diode," Proc. of the 13th International Conference on Infrared and Millimeter Waves, ed. by R.J. Temkin, pp. 5-6, Dec. 5-9, 1988.
5. S.M. Sze, Physics of Semiconductor Devices, 2nd ed., John Wiley & Sons, New York, 1981.
6. C.K. Peng, G.Ji, N.S. Kumar, and H. Morkoç, "Extremely low resistance nonalloyed ohmic contacts on GaAs using InAs/InGaAs and InAs/GaAs strained-layer superlattices," Appl. Phys. Lett., vol. 53, no. 10, pp. 900-902, 5 Sep. 1988.

I. LIST OF PUBLICATIONS (*JSEP Supported in whole or in part)

- * C.S. Kyono, V.P. Kesan, D.P. Neikirk, C.M. Maziar, and B.G. Streetman, "Dependence of Apparent Barrier Height on Barrier Thickness for Perpendicular Transport in AlAs/GaAs Single Barrier Structures Grown by MBE," Appl. Phys. Lett. 54, 6 Feb. 1989, pp. 549-551.
- * T.J. Mattord, V.P. Kesan, D.P. Neikirk, and B.G. Streetman, "A Single-filament Effusion Cell with Reduced Thermal Gradient for Molecular Beam Epitaxy," J. Vac. Sci. Technol. B 7, Mar/Apr 1989, pp. 214-216.

A. Dodabalapur, V.P. Kesan, T.R. Block, D.P. Neikirk, and B.G. Streetman, "Optical and Electrical Characterization of Pseudomorphic AlGaAs/InGaAs/GaAs Modulation-doped Structures Processed by Rapid Thermal Annealing," J. Vac. Sci. Technol. B 7, March/April 1989, pp. 380-383.

- * A. Dodabalapur, V.P. Kesan, D.R. Hinson, D.P. Neikirk, and B.G. Streetman, "Photoluminescence Studies of Pseudomorphic modulation-doped AlGaAs/ InGaAs/ GaAs Quantum Wells," Appl. Phys. Lett. 54, 24 April 1989, pp. 1675-1677.

- * R. L. Rogers and D. P. Neikirk, "Radiation properties of slot and dipole elements on layered substrates," International J. Infrared and Millimeter Waves, Vol.10, No.6, pp.697-728, (June 1989).

S. M. Wentworth, D. P. Neikirk, and C. R. Brahce, "The High Frequency Characteristics of Tape Automated Bonding (TAB) Interconnects," IEEE. Trans. Components, Hybrids, and Manufacturing Tech. 12, Sept. 1989, pp. 340-347

P. Cheung, D.P. Neikirk and T. Itoh, "A Schottky-biased, optically controlled coplanar waveguide phase shifter," Electronics Letters, Vol. 25, No. 19, pp. 1301-1302, (Sept. 14, 1989).

- * V. P. Kesan, A. Mortazawi, D. P. Neikirk and T. Itoh, "Conversion gain using a quantum well diode self-oscillating mixer," submitted to Electronics Letters.
- * V. P. Kesan, A. Mortazawi, D. R. Miller, V. K. Reddy, D. P. Neikirk and T. Itoh, "Microwave and millimeter wave QWITT diode oscillator," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 12, (Dec. 1989).

P. Cheung, D.P. Neikirk and T. Itoh, "Optically controlled coplanar waveguide phase shifter," (Invited paper), IEEE Transactions Microwave Theory and Techniques, (Special issue on applications of lightwave technology to microwave devices, circuits and systems).

- * A.C. Campbell, V.P. Kesan, T.R. Block, G.E. Crook, D.P. Neikirk, and B.G. Streetman, "Influence of MBE Growth Temperature on GaAs/AlAs Resonant Tunneling Structures," Journal of Electronic Materials 18, 1989, pp. 585-588.

II. LIST OF CONFERENCE PROCEEDINGS (*JSEP Supported in whole or in part)

- * "Microwave and millimeter wave QWITT oscillator," 1989 IEEE MTT-S International Microwave Symposium Digest, pp. 487-490, June 13-15, 1989, Long Beach, CA, (V. P. Kesan, A. Mortazawi, D. P. Neikirk and T. Itoh).
- "An optically controlled coplanar waveguide phase-shifter," 1989 IEEE MTT-SS International Microwave Symposium Digest, pp. 307-309, June 13-15, 1989, Long Beach, CA, (P. Cheung, D.P. Neikirk and T. Itoh).
- * "A self-oscillating QWITT diode mixer," 19th European Microwave Conference, pp. 715-718, September 4-7, 1989, London, England, (A. Mortazawi, V. P. Kesan, D. P. Neikirk and T. Itoh).
- * "Impedance measurements and calculations of a microstrip-fed slot antenna on a multilayered electrically thick dielectric substrate," 19th European Microwave Conference, pp. 167-171, September 4-7, 1989, London, England, (R. L. Rogers, D. P. Neikirk and T. Itoh).
- * "DC and microwave characterization of the quantum well injection transit time (QWITT) diode," International Symposium on Signals, Systems and Electronics, pp. 195-198,

(Page 7, Res. Unit SSE89-5, "Heterostructure Device Development")

September 18-20, 1989, Erlangen, W. Germany, (V. P. Kesan, A. Mortazawi, D. P. Neikirk and T. Itoh).

* "A twin slot antenna structure on a layered substrate for millimeter wave imaging arrays," 14th International Conference on Infrared and Millimeter Waves, pp. 399-400, Oct. 2-6, 1989, Wuerzburg, W. Germany, (S.M Wentworth, R.L. Rogers, D.P. Neikirk, and T. Itoh).

III. LIST OF PRESENTATIONS (*JSEP Supported in whole or in part)

* "The quantum well injection transit time diode," Engineering Foundation Conference on Advanced Heterostructure Transistors, Keauhou-Kona, Hawaii, Dec. 5-10, 1988 (D.P. Neikirk).

* "Microwave and millimeter wave QWITT oscillator," 1989 IEEE MTT-S International Microwave Symposium, June 13-15, 1989, Long Beach, CA, (V. P. Kesan, A. Mortazawi, D. P. Neikirk and T. Itoh).

"An optically controlled coplanar waveguide phase-shifter," 1989 IEEE MTT-SS International Microwave Symposium, June 13-15, 1989, Long Beach, CA, (P. Cheung, D.P. Neikirk and T. Itoh).

"Planar FET circuit for active antenna elements," International Symposium on Antennas and Propagation, August 22-25, 1989, Tokyo, Japan, (J. Birkeland and T. Itoh).

* "A self-oscillating QWITT diode mixer," 19th European Microwave Conference, September 4-7, 1989, London, England, (A. Mortazawi, V.P. Kesan, D.P. Neikirk and T. Itoh).

* "DC and microwave characterization of the quantum well injection transit time (QWITT) diode," International Symposium on Signals, Systems and Electronics, September 18-20, 1989, Erlangen, W. Germany, (V.P. Kesan, A. Mortazawi, D.P. Neikirk and T. Itoh).

"A twin slot antenna structure on a layered substrate for millimeter wave imaging arrays," 14th International Conference on Infrared and Millimeter Waves, pp. 399-400, Oct. 2-6, 1989, Wuerzburg, W. Germany.

IV. LIST OF THESES AND DISSERTATIONS (*JSEP Supported in whole or in part)

Master of Science

David Leason, "Characterization of Thin Films on Semi-insulating GaAs via Microwave Reflectometry," Spring 1989 (D. P. Neikirk, Supervisor).

Ph.D.

* Vijay P. Kesan, "Quantum well devices for microwave and millimeter wave oscillator applications," May 1989 (D. P. Neikirk, Supervisor).

(Page 8, Res. Unit SSE89-5, "Heterostructure Device Development")

- * Robert Lowell Rogers, "A study of slot and dipole antennas on layered electrically thick substrates for far infrared and millimeter wave imaging arrays," May 1989 (D. P. Neikirk, Supervisor).

Tom Linton, "Analysis of Three-Dimensional Effects in Advanced VLSI Devices," May 1989 (D. P. Neikirk, Supervisor).

V. GRANTS AND CONTRACTS

Air Force Office of Scientific Research Contract AF0SR-86-0036, "Monolithic Phase Shifter Study," Professors D. P. Neikirk and T. Itoh, Co-Principal Investigators.

IBM Corp., "IBM Faculty Development Award," Professor D. P. Neikirk, Principal Investigator.

National Science Foundation, "Presidential Young Investigator Award," Professor D. P. Neikirk, Principal Investigator.

3M Corporation, "3M Nontenured Faculty Grant," Professor D. P. Neikirk, Principal Investigator.

Texas Instruments, "A Study of Molecular Beam Epitaxial Growth of $\text{Ga}_x\text{In}_{1-x}\text{As}$ for Non-Alloyed Ohmic Contacts to GaAs," Professor D. P. Neikirk, Principal Investigator.

Texas Advanced Technology Program, "Heterostructure Tunneling Devices for Ultra-High Speed Device Applications," Professors D. P. Neikirk and B. G. Streetman, Co-Principal Investigators.

Texas Advanced Research Program, "Quantum Transport Studies and Double Barrier Heterostructures," Professor D. P. Neikirk, Principal Investigator.

| Structure | V_p (V) | ΔV (V) | J_p kA/cm^2 | ΔJ kA/cm^2 | peak to valley ratio | Specific Negative Resistance $\Omega\text{-cm}^2$ |
|---|--------------|-------------------|---------------------------|--------------------------------|-------------------------------|--|
| (A) 50Å spacer $W = 500\text{\AA}$ 5×10^{16} | 2.5 | 0.3 | 26 | 12 | 1.8 | 2.6×10^{-5} |
| (B) 50Å spacer $W = 1000\text{\AA}$ 5×10^{16} | 4.6 | 0.5 | 30 | 13 | 1.8 | 3.9×10^{-5} |
| (C) 50Å spacer $W = 2000\text{\AA}$ 5×10^{16} | 5.1 | 1.0 | 28 | 14 | 2.0 | 6.8×10^{-5} |
| (D) symmetric RTD | 0.88 | 0.34 | 20 | 11 | 2.2 | 3.1×10^{-5} |

Table I: DC characteristics for QWITT devices with uniformly doped depletion regions, A through D; W is the depletion layer thickness, V_p is the peak voltage, ΔV is the peak-to-valley voltage difference, J_p is the peak current density, and ΔJ is the peak-to-valley current density difference.

| Structure | V_p (V) | ΔV (V) | J_p kA/cm^2 | ΔJ kA/cm^2 | peak to valley ratio | Specific Negative Resistance $\Omega\text{-cm}^2$ |
|---|--------------|-------------------|---------------------------|--------------------------------|-------------------------------|--|
| (E) 100Å spike 5×10^{16} $W = 1800\text{\AA}$ | 3.5 | 1.1 | 31 | 19 | 2.5 | 5.8×10^{-5} |
| (F) 100Å spike 8×10^{16} $W = 1800\text{\AA}$ | 2.6 | 1.2 | 28 | 17 | 2.6 | 7.0×10^{-5} |
| (G) 100Å spike 1×10^{17} $W = 1800\text{\AA}$ | 0.9 | 0.64 | 23 | 12 | 2.1 | 5.3×10^{-5} |
| (H) 100Å spike 5×10^{17} $W = 1800\text{\AA}$ | 0.64 | 0.34 | 21 | 12 | 2.3 | 2.8×10^{-5} |

Table II: DC characteristics for QWITT devices with a doping spike, E through H.

| Drift Region Length (GHz) | Specific Negative Resistance ($10^{-5} \Omega\text{-cm}^2$) | | Output Power | Oscillation Frequency (μW) |
|---|--|------------|-------------------|--|
| | Measured | Simulation | | |
| 500 Å (A) 6-8 | 2.6 | 2.4 | 3 240 (planar) | 8-12 6-8 275 (planar) |
| 1000 Å (B) | 3.9 | 3.7 | 10 | 8-12 |
| 2000 Å (C) 28-31 910 (planar) 6-8 | 6.8 | 5.9 | 30 | 8-12 30 |
| Symmetric RTD (D) | 3.1 | 2.7 | 1 | 8-12 |

Table III: Microwave and millimeter-wave performance of QWITT diode oscillators, A through D, in both waveguide and planar circuits; the measured negative resistance and that predicted by the small signal model are also given.

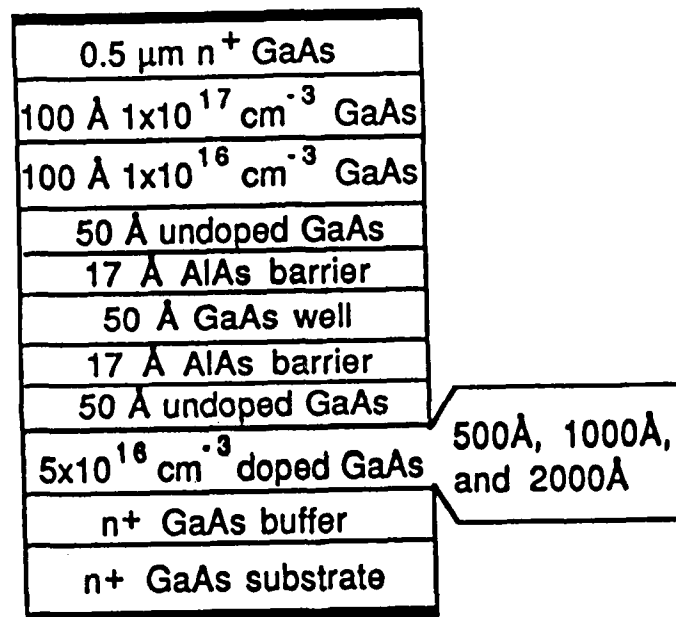


Fig. 1: A schematic cross section of the QWITT diode structures, A through D, examined in this study.

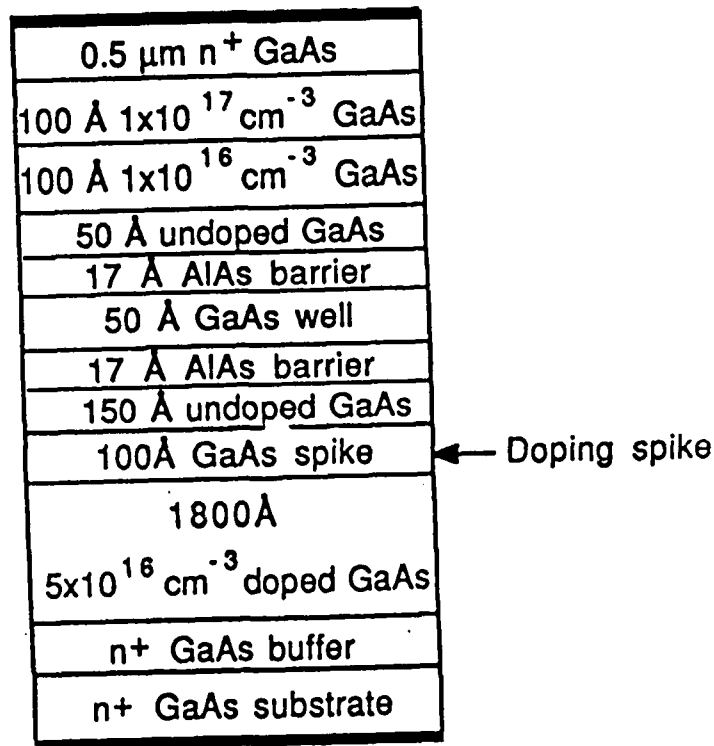


Fig. 2: A schematic cross section of the QWITT diode structures with a doping spike, E through H, examined in this study; the Si doping in the spike was varied between 5×10^{16} and $5 \times 10^{17} \text{ cm}^{-3}$.

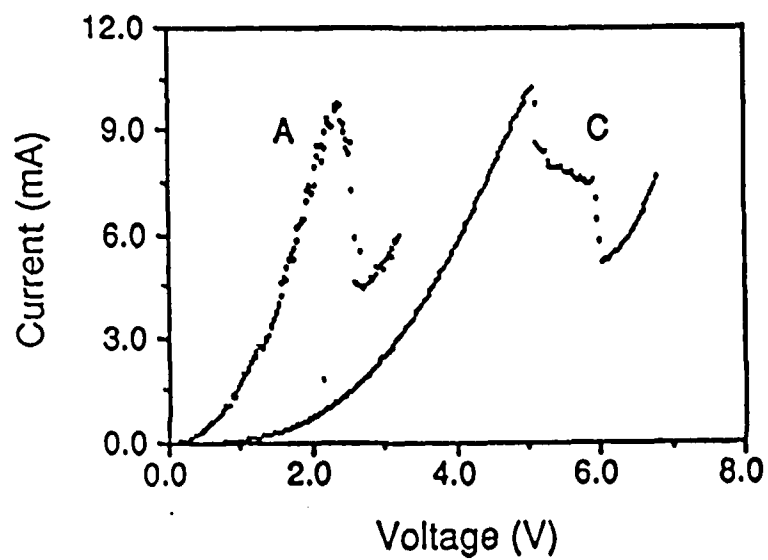


Fig. 3: Room temperature dc I-V curves for QWITT devices A and C with 500 Å and 2000 Å depletion region lengths, respectively.

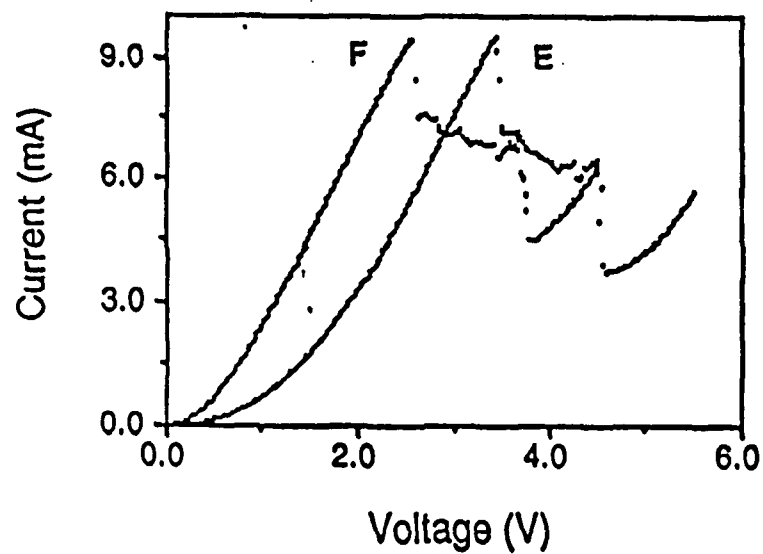


Fig. 4: Room temperature dc I-V curves for QWITT devices E and F with a Si doping spike of $5 \times 10^{16} \text{ cm}^{-3}$ and $1 \times 10^{17} \text{ cm}^{-3}$, respectively.

III. ELECTROMAGNETICS

Research Unit EM89-1: MILLIMETER WAVE ACTIVE GUIDED WAVE STRUCTURES

Principal Investigators: Professor T. Itoh (471-1072)
Professor D. P. Neikirk (471-4669)

Graduate Students: J. Birkeland, A. Mortazawi, C. W. Kuo, R. Rogers, V. Kesan, V. Reddy,
M. S. Islam

A. SCIENTIFIC OBJECTIVES: The primary objective is to conceive and develop novel circuit configurations for new solid state devices for millimeter-wave integrated oscillator structures. These circuit structures are intended to provide an electromagnetic environment that maximizes the potential capability of the solid state device. The secondary objective is to characterize these nonlinear active millimeter-wave circuits for a better understanding of the electromagnetic wave interactions of the devices with the microwave planar circuits so that a proper design procedure can be developed.

B. PROGRESS: The effort during this reporting period can be classified into three areas: (1) Development and characterizations of microwave oscillators using QWITT (Quantum Well Injection Transit Time) diodes, (2) Demonstration of a periodic diode oscillator, and (3) Planar antennas for coupling of the guided wave to free space. All of these three elements are integral parts leading to the development of a new class of millimeter-wave components in which the electromagnetic wave interaction with active devices makes optimum use of the device capability.

QWITT Diode Oscillator

The QWITT diode developed at The University of Texas is a quantum well diode consisting of a double barrier structure coupled with a drift region which increases the specific negative resistance and impedance of the device so that a higher output can be obtained [1]. The details of the configuration and the fabrication of the diode is described under the section "SSE89-5 Heterostructure Device Development" in this report. DC and microwave characteristics of the QWITT have been undertaken [2]. For the QWITT diodes with a uniformly doped drift region, devices with three different lengths of the drift regions, 500, 1000 and 2000 Å have been compared. In the DC characterization, the peak-to-valley current differences ΔI remains essentially unchanged with changing drift region, whereas the peak-to-valley voltage difference ΔV increases from 0.3 to 1.18 V. In addition, the increase of the voltage at peak current increases from 2.4 to 5.5 V when the length was increased from 500 to 2000 Å. Since microwave power output depends on the $\Delta V \Delta I$ product, output should be higher in the 2000 Å device compared to devices with shorter drift regions. This fact was confirmed in the microwave oscillator experiments described below. In addition to the uniformly doped device, diodes with a doping spike in the drift region were also tested. It was found that an appropriate spike configuration increases the DC to RF efficiency with a moderate increase of the output power. This is because the voltage for the peak current decreases without changing ΔV and ΔI very much [3,4,5]. Further details are discussed in section "SSE89-5."

Microwave experiments were conducted in a waveguide cavity, as well as in a planar microwave integrated circuit (MIC) configuration. The configuration of the waveguide and MIC oscillator circuits are shown in Fig.1. In the waveguide version, a whisker-contacted diode mounted on a movable post is mounted in a WR-90 waveguide backed with a sliding short. The oscillation frequency has been varied from 8 ~ 12 GHz by adjusting the bias and the mounting structure. Output power was optimized by adjusting the sliding short. The output power of the waveguide oscillator with 500, 1000 and 2000 Å devices was 3, 10 and 30 μ W, respectively. With the MIC configuration, the output from the 2000 Å device was 910 μ W at a frequency between 6 and 8 GHz. This is primarily caused by the impedance of the planar circuit which is much lower than that of the waveguide circuit. This value is the highest output ever recorded with any quantum well oscillator. In addition, this is the first planar quantum well oscillator. A millimeter-wave oscillation has also been obtained in the structure with a WR-22 waveguide at 28 ~ 31 GHz. The output was found to be 30 μ W with the same device used in the X band experiments [3,4,5].

We also investigated the use of a QWITT diode as a self-oscillating mixer. This structure takes advantage of the nonlinear nature of the QWITT. The device is used as the oscillator and the mixer simultaneously. The X-band waveguide mixer exhibited a conversion gain of about 10 dB in a narrow bandwidth (10 ~ 20 MHz), and a conversion loss of about 3-5 dB over a broad bandwidth. The planar MIC circuit exhibited a narrow band conversion gain of 4 dB or a broad band conversion loss of 8-10 dB [5,6]. To the best of our knowledge, this is the only report of conversion gain ever obtained from a self-oscillating mixer using a quantum well device, indicating the possibility of integration of mixer and LO functions.

Periodic Diode Oscillator

Planar oscillators in MIC or MMIC/MIMIC (Monolithic Microwave Integrated Circuit/Monolithic Millimeter-Wave Integrated Circuit) suffer two problems. One is the lack of high Q resonator components and another is the limitation of output power. The usual solution of the first problem is the use of a dielectric resonator which defeats the purpose of a planar circuit and cannot be used in MMIC/MIMIC environment. A printed resonator such as a microstrip patch has a low Q and is potentially radiative. The second problem becomes increasingly severe as the operating frequencies are increased. One solution is a power combining of multiple oscillators. However, the conventional power combining of the circuit level and device level requires a very intricate design.

In order to overcome these two problems simultaneously, the concept of periodic oscillators has been introduced [7]. In this scheme, a transmission line is loaded periodically with several active devices with appropriate impedance elements. The physical distance of the period is chosen such that it is one half of the guide wavelength along the transmission line at the desired frequency of oscillation. Due to the stopband phenomenon in a periodic structure, the oscillation frequency of each device is locked at such a frequency. Therefore, the periodic structure works as a resonant configuration. At the same time the oscillation output from all devices are combined to generate a higher output power. The Q of the resonant configuration and the overall output power increase as the number of devices is increased up to a certain practical limit.

A structure demonstrating this concept has been built with a Gunn diode as shown in Fig.2 [8]. Oscillators with up to six diodes have been built and tested at X band. In the design, the large signal impedance of each diode has been measured by constructing a single diode circuit. The reactive part of the impedance was tuned out by the use of an inductive stub as shown in the figure. This process makes the main transmission line loaded periodically with pure negative resistances. The combining efficiency of the periodic oscillator exceeded in the case of two, three, five diodes and were 119, 127 and 121%, respectively. This means that the output from

these structures is larger than two, three and five times the single device oscillator. This phenomenon is understood to be caused by the nonlinearity of the device so that the environment of the multiple device oscillators is different from that of the single device structure. For six diode cases, the efficiency was reduced to 90%.

This project clearly demonstrated the importance and usefulness of the wave-device interactions for development of the useful high frequency components.

Integrated Twin Slot Antennas

At higher frequencies, integrated antennas are essential elements for interfacing oscillators and mixers in receiver circuits with free space. Because of the small wavelengths involved it may be necessary to use an electrically thick substrate to support the antennas and device circuitry. A method for analyzing such a structure has been developed and the theory experimentally confirmed [9,10]. It was found that a layered substrate can be used for tailoring the antenna characteristics (both impedance and beam pattern). Twin-slot antennas fed by a microstrip line with a integrated bismuth microbolometers have now been tested at 95 GHz [11]. Twin slots were fabricated on a three layered quartz-air-quartz substrate. Each layer is $1/4$ wavelength thick to provide the impedance matching effect. The slots were covered with a thin insulating layer on which a feeding microstrip circuit (including the bolometer and low pass filters) was fabricated. The measured gain of this three layer configuration was higher by 6 dB, in agreement with the theory, than the identical antenna circuit fabricated on a single quartz substrate. Radiation patterns also exhibited near perfect agreement with the theoretical predictions. These structures should be appropriate for use in integrated millimeter wave imaging systems.

C. FOLLOW-UP STATEMENT: The three projects reported above will be continued with enhanced coordination. A periodic oscillator using QWITT diodes is the next goal. Additionally, higher frequency oscillation of a single diode circuit is planned using monolithic circuit techniques such as a E-plane (finline) configuration. On the other hand, the twin slot antenna combined with a self oscillating QWITT diode mixer is an exciting topic to be investigated. Throughout these projects, solid state devices must be investigated within an electromagnetic environment so that their utmost capability is extracted.

D. REFERENCES:

1. V. P. Kesan, D. P. Neikirk, B. G. Streetman and P. A. Blakey, "A new transit time device using quantum well injection," IEEE Elect. Dev. Lett., Vol. EDL-8, No.4, pp.129-131, (April 1987).
2. V. P. Kesan, A. Mortazawi, D. R. Miller, T. Itoh, B. G. Streetman and D. P. Neikirk, "Microwave frequency operation of the quantum well injection transit time (QWITT) diode," Electronics Letters, Vol.24, No.24, pp.1473-1474, (November 24, 1988).
3. V. P. Kesan, A. Mortazawi, D. P. Neikirk and T. Itoh, "Microwave and millimeter wave QWITT oscillator," 1989 IEEE MTT-S International Microwave Symposium Digest, pp.487-490, Long Beach, CA, (June 13-15, 1989).

4. V. P. Kesan, A. Mortazawi, D. P. Neikirk and T. Itoh, "DC and microwave characterization of the quantum well injection transit time (QWITT) diode," International Symposium on Signals, Systems and Electronics, pp.195-198, September 18-20, 1989, Erlangen, W. Germany.
5. V. P. Kesan, A. Mortazawi, D. R. Miller, V. K. Reddy, D. P. Neikirk and T. Itoh, "Microwave and millimeter wave QWITT diode oscillator," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No.12, (December 1989).
6. A. Mortazawi, V. P. Kesan, D. P. Neikirk and T. Itoh, "A self-oscillating QWITT diode mixer," 19th European Microwave Conference, pp.715-718, September 4-7, 1989, London, England.
7. V. P. Kesan, A. Mortazawi, D. P. Neikirk and T. Itoh, "Monolithic millimeter-wave oscillator using a transmission line periodically loaded by QWITT diodes," Electronics Letters, Vol.24, No.11, pp.666-667, (May 26, 1988).
8. A. Mortazawi and T. Itoh, "A periodic planar Gunn diode power combining oscillator," to appear in IEEE Trans. Microwave Theory and Techniques, Vol.38, No.1, (January 1990).
9. R. L. Rogers and D. P. Neikirk, "Radiation properties of slot and dipole elements on layered substrates," International J. Infrared and Millimeter Waves, Vol.10, No.6, pp.697-728, (June 1989).
10. R. L. Rogers, D. P. Neikirk and T. Itoh, "Impedance measurements and calculations of a microstrip-fed slot antenna on a multilayered electrically thick substrate," 19th European Microwave Conference, pp.167-171, September 4-7, 1989, London, England.
11. S. M. Wentworth, R. L. Rogers, D. P. Neikirk and T. Itoh, "A twin slot antenna structure on a layered substrate for millimeter wave imaging arrays," 14th International Conference on Infrared and Millimeter Waves," pp.399-400, October 2-6, 1989, Wuerzburg, W. Germany.

I. LIST OF PUBLICATIONS (*JSEP Supported in whole or in part)

- * R. L. Rogers and D. P. Neikirk, "Radiation properties of slot and dipole elements on layered substrates," International J. Infrared and Millimeter Waves, Vol.10, No.6, pp.697-728, (June 1989).
- * T. Itoh, "Overview of quasi-planar transmission lines," (Invited) IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 2, pp. 275-280, (Feb. 1989).

H.-Y. Lee and T. Itoh, "GaAs traveling-wave optical modulator using a modulated coplanar strip electrode with periodic cross-tie overlay," Int. J. Infrared and Millimeter Waves, Vol. 10, No. 3, pp. 321-335, (March 1989).

S. Nam, H. Ling and T. Itoh, "Time-domain method of lines applied to planar guided wave structure," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 5, pp. 897-901, (May 1989).

A. D. Brouman, H. Ling and T. Itoh, "Transmission properties of a right-angle microstrip bend with and without a miter," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 5, pp. 925-929, (May 1989).

S. El-Ghazaly and T. Itoh, "Analysis of travelling-wave inverted-gate microwave field-effect transistors," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 6, pp. 1027-1032, (June 1989).

J. Birkeland and T. Itoh, "Planar FET oscillators using periodic microstrip patch antennas," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 8, pp. 1232-1236, (Aug. 1989).

J. Birkeland and T. Itoh, "FET-based planar circuits for quasi-optical sources and transceivers," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 9, (Sept. 1989).

T. Itoh, "Recent progress of quasi-optical integrated microwave and millimeter wave circuits and components," to appear in Alta Frequenza, Vol. 57, (August 1989).

V. P. Kesan, A. Mortazawi, D. P. Neikirk and T. Itoh, "Conversion gain using a quantum well diode self-oscillating mixer," submitted to Electronics Letters.

* A. Mortazawi and T. Itoh, "A periodic planar Gunn diode power combining oscillator," to appear in IEEE Trans. Microwave Theory and Techniques.

* V. P. Kesan, A. Mortazawi, D. R. Miller, V. K. Reddy, D. P. Neikirk and T. Itoh, "Microwave and millimeter wave QWITT diode oscillator," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 12, (Dec. 1989).

* T. Itoh, "Recent advances in numerical methods for microwave and millimeter-wave passive structures," IEEE Trans. Magnetics, Vol. 25, No. 4, pp. 2931-2934, (July 1989).

S. Nam, H. Ling and T. Itoh, "Characterization of uniform microstrip line and its discontinuities using time-domain method of lines," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 12, (December 1989).

K. S. Kong and T. Itoh, "Computer aided design of evanescent mode waveguide bandpass filter with non-touching E-plane fins," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 12, (December 1989).

H.-Y. Lee and T. Itoh, "Phenomenological loss equivalent method for planar quasi-TEM transmission lines with a thin normal conductor or superconductor," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 12, (December 1989).

C.Y. Chang and T. Itoh, "Narrow-band planar microwave active filter," Electronics Letters, Vol. 25, No. 18, pp. 1228-1229, (Aug. 31, 1989).

P. Cheung, D.P. Neikirk and T. Itoh, "A Schottky-biased, optically controlled coplanar waveguide phase shifter," Electronics Letters, Vol. 25, No. 19, pp. 1301-1302, (Sept. 14, 1989).

P. Cheung, D.P. Neikirk and T. Itoh, "Optically controlled coplanar waveguide phase shifter," (Invited paper), IEEE Transactions Microwave Theory and Techniques, (Special issue on applications of lightwave technology to microwave devices, circuits and systems).

II. LIST OF CONFERENCE PROCEEDINGS (*JSEP Supported in whole or in part)

"On the potential of the traveling-wave inverted-gate field-effect transistors," National Radio Science Meeting, pp. D-1-1, January 4-6, 1989, Boulder, CO, (T. Itoh and S. El-Ghazaly).

"Progress in microstrip-based quasi-optical circuits," National Radio Science Meeting, pp. DB-1-1, January 4-6, 1989, Boulder, CO (J. Birkeland and T. Itoh).

"Application of coplanar transmission line structures for microwave-optical interaction circuits," MIOP 89, pp. 5B-1, Feb. 28-March 2, 1989, Sindelfingen, W. Germany (T. Itoh).

"Recent developments in optically generated slow wave phenomena," Melecon'89, April 11,13-1989, Lisbon Portugal, (T. Itoh).

"Quasi-optical planar FET transceiver modules," 1989 IEEE MTT-S International Microwave Symposium Digest, pp. 119-122, June 13-15, 1989, Long Beach, CA, (J. Birkeland and T. Itoh).

- * "Microwave and millimeter wave QWITT oscillator," 1989 IEEE MTT-S International Microwave Symposium Digest, pp. 487-490, June 13-15,1989, Long Beach, CA, (V. P. Kesan, A. Mortazawi, D. P. Neikirk and T. Itoh).

"Wideband conductor loss calculation of planar quasi-TEM transmission lines with thin conductors using a phenomenological loss equivalence method," 1989 IEEE MTT-S International Microwave Symposium Digest, pp. 367-370, June 13-15,1989, Long Beach, CA, (H.-Y. Lee and T. Itoh).

"Computer aided design of evanescent mode waveguide bandpass filter with non-touching E-plane fins," 1989 IEEE MTT-S International Microwave Symposium Digest, pp. 1159-1162, June 13-15, 1989, Long Beach, CA, (K. S. Kong and T. Itoh).

"An optically controlled coplanar waveguide phase-shifter," 1989 IEEE MTT-SS International Microwave Symposium Digest, pp. 307-309, June 13-15, 1989, Long Beach, CA, (P. Cheung, D.P. Neikirk and T. Itoh).

Waveform-balance method for nonlinear MESFET amplifier simulation," 1989 MTT-S International Microwave Symposium Digest, pp. 581-584, June 13-15, 1989, Long Beach, CA, (V.D. Hwang and T. Itoh).

"Characterization of uniform microstrip line and its discontinuities using time-domain method of lines," 1989 IEEE MTT-S International Microwave Symposium Digest, pp.999-1000, June 13-15, 1989, Long Beach, CA (S. Nam, H. Ling and T. Itoh).

"Progress of transverse resonance technique for printed transmission line structures," Progress in Electromagnetics Research Symposium, July 25-27, 1989, Boston, MA, (T. Itoh).

"Planar FET circuit for active antenna elements," International Symposium on Antennas and Propagation, pp. 277-280, August 22-25, 1989, Tokyo, Japan, (J. Birkeland and T. Itoh).

- * "A self-oscillating QWITT diode mixer," 19th European Microwave Conference, pp. 715-718, September 4-7, 1989, London, England, (A. Mortazawi, V. P. Kesan, D. P. Neikirk and T. Itoh).

"Computer aided design for planar microstrip circuit analysis by boundary-integral method," 19th European Microwave Conference, pp. 975-978, September 4-7, 1989, London, England, (S. Chang, W.-X. Huang and T. Itoh).

"Characterization of the coplanar waveguide step discontinuity using the transverse resonance method," 19th European Microwave Conference, pp. 662-665, September 4-7, 1989, London, England, (C.-W. Kuo and T. Itoh).

- * "Impedance measurements and calculations of a microstrip-fed slot antenna on a multilayered electrically thick dielectric substrate," 19th European Microwave Conference, pp. 167-171, September 4-7, 1989, London, England, (R. L. Rogers, D. P. Neikirk and T. Itoh).

"A microstrip based active antenna Doppler transceiver module," 19th European Microwave Conference, pp. 172-175, September 4-7, 1989, London, England, (J. Birkeland and T. Itoh).

"Conductor loss calculation of superconductor microstrip line using a phenomenological loss equivalence method," 19th European Microwave Conference, pp. 757-760, September 4-7, 1989, London, England, (H. -Y. Lee, K. -S. Kong and T. Itoh).

- * "DC and microwave characterization of the quantum well injection transit time (QWITT) diode," International Symposium on Signals, Systems and Electronics, pp. 195-198, September 18-20, 1989, Erlangen, W. Germany, (V. P. Kesan, A. Mortazawi, D. P. Neikirk and T. Itoh).

"Planar FET transceiver modules for Doppler motion detection," (Invited) 14th International Conference on Infrared and Millimeter Waves, pp. 206-208, Oct. 2-6, 1989, Wuerzburg, W. Germany, (J. Birkeland and T. Itoh).

- * "A twin slot antenna structure on a layered substrate for millimeter wave imaging arrays," 14th International Conference on Infrared and Millimeter Waves, pp. 399-400, Oct. 2-6, 1989, Wuerzburg, W. Germany.

III. LIST OF PRESENTATIONS (*JSEP Supported in whole or in part)

"On the potential of the traveling-wave inverted-gate field-effect transistors," National Radio Science Meeting, pp. D-1-1, January 4-6, 1989, Boulder, CO (T. Itoh and S. El-Ghazaly).

"Progress in microstrip-based quasi-optical circuits," National Radio Science Meeting, pp. DB-1-1, January 4-6, 1989, Boulder, CO (J. Birkeland and T. Itoh).

"Application of coplanar transmission line structures for microwave-optical interaction circuits," MIOP 89, pp. 5B-1, Feb. 28-March 2, 1989, Sindelfingen, W. Germany (T. Itoh).

"Recent developments in optically generated slow wave phenomena," Melecon'89, April 11,13-1989, Lisbon Portugal, (T. Itoh).

"Quasi-optical planar FET transceiver modules," 1989 IEEE MTT-S International Microwave Symposium, June 13-15, 1989, Long Beach, CA, (J. Birkeland and T. Itoh).

- * "Microwave and millimeter wave QWITT oscillator," 1989 IEEE MTT-S International Microwave Symposium, June 13-15, 1989, Long Beach, CA, (V. P. Kesan, A. Mortazawi, D. P. Neikirk and T. Itoh).

"Wideband conductor loss calculation of planar quasi-TEM transmission lines with thin conductors using a phenomenological loss equivalence method," 1989 IEEE MTT-S International Microwave Symposium, June 13-15, 1989, Long Beach, CA, (H.-Y. Lee and T. Itoh).

"Computer aided design of evanescent mode waveguide bandpass filter with non-touching E-plane fins," 1989 IEEE MTT-S International Microwave Symposium, June 13-15, 1989, Long Beach, CA, (K. S. Song and T. Itoh).

"An optically controlled coplanar waveguide phase-shifter," 1989 IEEE MTT-SS International Microwave Symposium, June 13-15, 1989, Long Beach, CA, (P. Cheung, D.P. Neikirk and T. Itoh).

"Waveform-balance method for nonlinear MESFET amplifier simulation," 1989 MTT-S International Microwave Symposium, June 13-15, 1989, Long Beach, CA, (V.D. Hwang and T. Itoh).

"Characterization of uniform microstrip line and its discontinuities using time-domain method of lines," 1989 IEEE MTT-S International Microwave Symposium, June 13-15, 1989, Long Beach, CA (S. Nam, H. Ling and T. Itoh).

"Progress of transverse resonance technique for printed transmission line structures," Progress in Electromagnetics Research Symposium, July 25-27, 1989, Boston, MA, (T. Itoh).

"Planar FET circuit for active antenna elements," International Symposium on Antennas and Propagation, August 22-25, 1989, Tokyo, Japan, (J. Birkeland and T. Itoh).

- * "A self-oscillating QWITT diode mixer," 19th European Microwave Conference, September 4-7, 1989, London, England, (A. Mortazawi, V.P. Kesan, D.P. Neikirk and T. Itoh).

"Computer aided design for planar microstrip circuit analysis by boundary-integral method," 19th European Microwave Conference, September 4-7, 1989, London, England, (S. Chang, W.-X. Huang and T. Itoh).

"Characterization of the coplanar waveguide step discontinuity using the transverse resonance method," 19th European Microwave Conference, September 4-7, 1989, London, England, (C.-W. Kuo and T. Itoh).

- * "Impedance measurements and calculations of a microstrip-fed slot antenna on a multilayered electrically thick dielectric substrate," 19th European Microwave Conference, September 4-7, 1989, London, England, (H.-Y. Lee, K.-S. Kong and T. Itoh).

"Conductor loss calculation of superconductor microstrip line using a phenomenological loss equivalence method," 19th European Microwave Conference, September 4-7, 1989, London, England, (H.-Y. Lee, K.-S. Kong and T. Itoh).

- * "DC and microwave characterization of the quantum well injection transit time (QWITT) diode," International Symposium on Signals, Systems and Electronics, September 18-20, 1989, Erlangen, W. Germany, (V.P. Kesan, A. Mortazawi, D.P. Neikirk and T. Itoh).

"Planar FET transceiver modules for Doppler motion detection," (Invited) pp. 195-198, Oct. 2-6, 1989, Wuerzburg, W. Germany, (J. Birkeland and T. Itoh).

"A twin slot antenna structure on a layered substrate for millimeter wave imaging arrays," 14th International Conference on Infrared and Millimeter Waves, pp. 399-400, Oct. 2-6, 1989, Wuerzburg, W. Germany.

IV. LIST OF THESES AND DISSERTATIONS (*JSEP Supported in whole or in part)

Master of Science

Chih-Wen Kuo, "Characterization of coplanar waveguide discontinuities using the transverse resonance method," May 1989 (T. Itoh, Supervisor).

Afroditi Vennie Filippas, "Mode matching analysis of the coplanar microstrip line," May 1989 (T. Itoh, Supervisor).

David Leason, "Characterization of Thin Films on Semi-insulating GaAs via Microwave Reflectometry," Spring 1989 (D. P. Neikirk, Supervisor).

Ph.D.

Sangwook Nam, "A study of a new time-domain method of lines and its application for the characterization of microstrip line and its discontinuities," May 1989 (T. Itoh, Supervisor).

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- * Vijay P. Kesan, "Quantum well devices for microwave and millimeter wave oscillator applications," May 1989 (D. P. Neikirk, Supervisor).
- * Robert Lowell Rogers, "A study of slot and dipole antennas on layered electrically thick substrates for far infrared and millimeter wave imaging arrays," May 1989 (D. P. Neikirk, Supervisor).

Tom Linton, "Analysis of Three-Dimensional Effects in Advanced VLSI Devices," May 1989 (D. P. Neikirk, Supervisor).

Joel David Birkeland, "Planar integrated circuits for microwave transmission and reception," August 1989 (T. Itoh, Supervisor).

V. GRANTS AND CONTRACTS

Office of Naval Research Contract N0000-79-C-0553, "Millimeter Wave Transmission Lines," Professor T. Itoh, Principal Investigator.

Air Force Office of Scientific Research Contract AF0SR-86-0036, "Monolithic Phase Shifter Study," Professors D. P. Neikirk and T. Itoh, Co-Principal Investigators.

IBM Corp., "IBM Faculty Development Award," Professor D. P. Neikirk, Principal Investigator.

National Science Foundation, "Presidential Young Investigator Award," Professor D. P. Neikirk, Principal Investigator.

3M Corporation, "3M Nontenured Faculty Grant," Professor D. P. Neikirk, Principal Investigator.

Texas Instruments, "A Study of Molecular Beam Epitaxial Growth of $GaxIn_{1-x}As$ for Non-Alloyed Ohmic Contacts to GaAs," Professor D. P. Neikirk, Principal Investigator.

Army Research Office Contract, DAAL03-88-K-0005, "Guided Wave Phenomena in Millimeter Wave Integrated Circuits and Components," Professor T. Itoh, Principal Investigator.

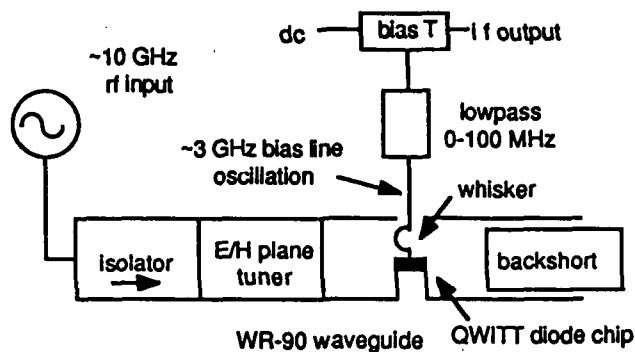
Office of Naval Research Grant, N00014-89-J-1006, "High Temperature Superconducting Planar Circuit Structures for High Frequency Applications," Professor T. Itoh, Principal Investigator.

Texas Advanced Technology Program, "Monolithic Millimeter-Wave Integrated Circuits," Professor T. Itoh, Principal Investigator.

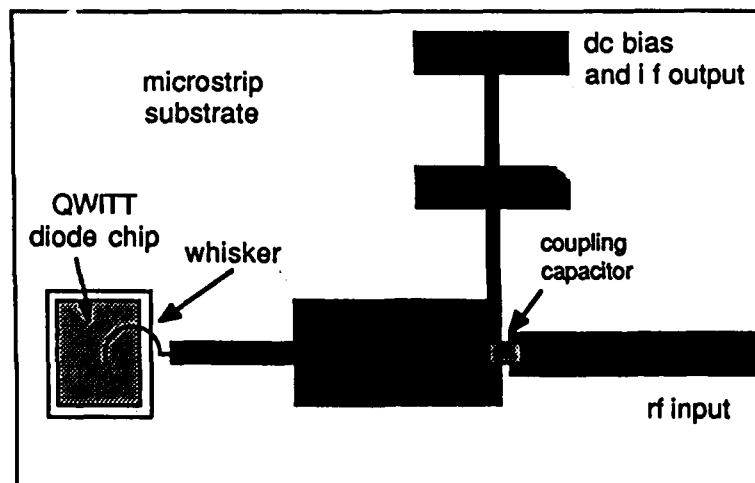
Texas Advanced Technology Program, "Computer Aided Design of Millimeter-Wave Integrated Circuits," Professors T. Itoh and H. Ling, Co-Principal Investigators.

Texas Advanced Technology Program, "Heterostructure Tunneling Devices for Ultra-High Speed Device Applications," Professors D. P. Neikirk and B. G. Streetman, Co-Principal Investigators.

Texas Advanced Research Program, "Quantum Transport Studies and Double Barrier Heterostructures," Professor D. P. Neikirk, Principal Investigator.



(a)



(b)

Figure 1: (a) schematic diagram of waveguide circuit used for microwave testing of QWITT diodes; (b) planar microwave integrated circuit used with the QWITT diodes.

Research Unit EM89-2: Nonlinear Wave Phenomena

Principal Investigator: Professor Edward J. Powers (512) 471-3954

Graduate Students: C. K. An and S. W. Nam

Research Associates: Dr. S. B. Kim and Dr. Ch. P. Ritz

A. SCIENTIFIC OBJECTIVES: The overall scientific objective of this research program is to conceive and implement novel digital time series analysis techniques that may be utilized to analyze and interpret experimental time series data associated with nonlinear wave interactions and related phenomena. The underlying philosophy is to concentrate on those high-risk canonical questions that are relevant to many areas of science and technology. Based on our past experience, we have found that the results of such studies have been readily transferable to a diversity of technical fields where nonlinear phenomena are important. Examples include nonlinear scattering, instabilities in high performance aircraft, underwater acoustics, energy cascading associated with transition to turbulence, and nonlinear signatures.

We are specifically concerned with answering the following questions given time series data characterizing a potentially nonlinear physical system:

- (1) How does one detect nonlinearities in the physical system that gave rise to the data?
- (2) How does one quantify the type of nonlinearity (e.g., quadratic or cubic) and the "strength" of the nonlinearity in various frequency bands?
- (3) Finally, can one further process the time series data to quantify the rate at which energy is being exchanged between various spectral bands as a result of the nonlinear interactions?

Our approach may be briefly summarized as follows. The presence of nonlinearities in the physical system that gave rise to the time series data may be detected using higher-order spectra, such as the bispectrum and trispectrum. Such spectra are sensitive to the phase coherence and, hence, correlation between various interacting frequencies resulting from either three-wave or four-wave interactions. To quantify the strength of the interaction, the fluctuation or wave field is measured at two closely spaced (with respect to wavelength and correlation length) spatial points, and the observed linear and nonlinear wave physics is modeled with the aid of a hierarchy of linear, quadratic, cubic, etc. transfer functions. These transfer functions can then be related, via the fundamental "equations of motion" governing the linear and nonlinear physics of the system, to the three-wave (quadratic) and four-wave (cubic) coupling coefficients. Experimental knowledge of the coupling coefficients is important, since the relevant physics is imbedded in the coupling coefficient. Furthermore, experimental knowledge of the nonlinear transfer functions and coupling coefficients is necessary in quantifying the rate and direction of energy transfer between various interacting waves or modes of the system. Under previous JSEP sponsorship, we have addressed all of these issues for quadratically nonlinear systems which, of course, give rise to three-wave interactions. Under current JSEP sponsorship, we are considering cubically nonlinear systems and associated four-wave interactions. Our progress is summarized in the next section.

B. PROGRESS: During the past twelve-month period, one triennial period ended and another began. Thus, the following summary will cover work carried out during both periods.

Three-Wave Interaction Phenomena: The goal of the triennium ending March 31, 1989 was to develop algorithms and to implement them digitally so that, given appropriate time series data, one can experimentally determine complex three-wave coupling coefficients and the resulting energy transfer.

As was briefly indicated in Sec. A, our approach is to model the linear and quadratically nonlinear wave physics occurring between two closely spaced points with the aid of linear and quadratically nonlinear transfer functions. Knowledge of the linear transfer function enables one to determine linear growth (or damping) rates and the dispersion relation, whereas, and most importantly, measurements of the quadratic transfer function enables one to determine the complex three-wave coupling coefficient. Knowledge of the three-wave coupling coefficient then permits comparison with theoretical values as well as determination of the energy transfer that occurs between waves (or modes) as a result of the three-wave interaction. With respect to determination of the nonlinear transfer functions, we found that it is extremely important to take into account the nonGaussianity of the time series data. In the case of noise or turbulence data, the nonGaussianity results from the nonlinear interactions that have occurred previously at other points in either space and/or time. It is for this reason that the phrase "nonGaussian" appears in the titles of so many of our publications.

In ref. [1], we present the methodology for determining quadratic transfer functions. The approach rests upon the innovative application of polyspectra [19], i.e., higher-order spectra. We have made what are, to the best of our knowledge, the first measurements of three-wave coupling coefficients from turbulent/noise-like data and have also quantified the energy transfer between all the interacting triads present in the fluctuation spectrum [3, 10, 14, 22].

Cubic Transfer Functions: During the current triennium, our ultimate goal is to measure four-wave coupling coefficients, which result from cubic nonlinearities. On the basis of our success in measuring three-wave coupling coefficients, the approach is conceptually straightforward. However, the degree of complexity is significantly increased because of the higher-order dimensionality of the situation. For example, cubic transfer functions and four-wave interaction coefficients are intrinsically three-dimensional functions of frequency. Consequently, the higher-order spectrum known as the trispectrum, and also a three-dimensional function of frequency, must be utilized. We have given a great deal of thought as to how to carry out the necessary computations and portray the results in three-dimensional space. Our initial results on the experimental determination of cubic transfer functions are presented in refs. [9, 21].

Other Applications: As was mentioned in Sec. A, SCIENTIFIC OBJECTIVES, we have found our ability to quantify nonlinear wave phenomena in terms of a hierarchy of linear and nonlinear transfer functions to exhibit tremendous technology transfer potential to many other areas of science and technology. In the following, we mention work supported by other agencies, but which make extensive use of capabilities originally developed under JSEP sponsorship. This fact is acknowledged in the references with a double asterisk. Specifically, we have found in work principally supported by NSF and the Texas Advanced Research Program that the bispectrum and the ability to measure quadratic transfer functions have proven to be powerful tools with which to quantify nonlinear phenomena associated with transition to turbulence in fluids [2, 5, 15, 16, 27]. These same concepts have also proven to be very powerful in quantifying the nonlinear response of ships (supported by ONR) and offshore structures (supported by NSF and the Texas Advanced Technology Program) to nonGaussian random seas [7, 8, 11, 12, 13, 18, 20, 23, 24, 25, 26]. Also, we mention that digital higher-order spectra and nonlinear transfer function concepts will be extensively utilized in a newly funded (by the Texas Advanced Technology Program) investigation of nonlinear aeroelastic phenomena associated with high performance aircraft. Commitments to provide wind tunnel or actual flight test data have been made by three

major U.S.A. aircraft companies. Finally, we observe that all the work cited above has been carried out in the frequency domain, since waves and their interactions are best viewed in terms of frequencies and wave numbers. This work has, however, motivated some time-domain studies of nonlinear system identification and has given rise to such concepts as second-order Volterra digital filters [6, 17] that appear to offer certain advantages when incorporated into various types of advanced control systems. Finally, we note an initial study dealing with optical computation of the bispectrum using acoustooptical modulators [4].

C. FOLLOW-UP STATEMENT: This work is continuing with primary focus on detection of four-wave interactions, experimental determination of cubic transfer functions and four-wave coupling coefficients, and measurement of energy transfer resulting from four-wave interactions, i. e., cubic nonlinearities.

I. LIST OF PUBLICATIONS (* denotes JSEP supported in whole or part; ** denotes a publication principally supported by another grant(s)/contract(s) in which JSEP is acknowledged for its nonlinear signal processing contributions.)

- *1. K. I. Kim and E. J. Powers, "A Digital Method of Modeling Quadratically Nonlinear Systems with a General Random Input," IEEE Transactions on Acoustics, Speech, and Signal Processing, **36**, 1758-1769, November 1988.
- **2. Ch. P. Ritz, E. J. Powers, R. W. Miksad, and R. S. Solis, "Nonlinear Spectral Dynamics of a Transitioning Flow," Physics of Fluids, **31**, 3577-3588, December 1988.
- *3. Ch. P. Ritz, E. J. Powers, and R. D. Bengtson, "Experimental Measurements of Three-Wave Coupling and Energy Cascading," Physics of Fluids, **B1**, 153-163, January 1989.
4. M. H. Kauderer, M. F. Becker, and E. J. Powers, "Acoustooptical Bispectral Processing," Applied Optics, **28**, 627-637, February 1, 1989.

II. LIST OF CONFERENCE PROCEEDINGS (* denotes JSEP supported in whole or in part; ** denotes a publication principally supported by another grant(s)/contract(s) but in which JSEP is acknowledged for its nonlinear signal processing contributions.)

- **5. R. W. Miksad, M. R. Hajj, and E. J. Powers, "Measurement of Nonlinear Transfer Functions for Subharmonic Generation in Mixing Layers," paper AIAA 89-0980 from AIAA 2nd Shear Flow Conference, Tempe, Arizona, March 13-16, 1989, 6pp.
- **6. K. H. Kim, S. B. Kim, E. J. Powers, and R. W. Miksad, "Application of Second-Order Volterra Digital Filters to Low Frequency Drift Oscillation Phenomena," Proceedings of the Eighth International Conference on Offshore Mechanics and Arctic Engineering, Vol. 1, The Hague, The Netherlands, 533-537, March 19-23, 1989.
- **7. S. B. Kim, E. J. Powers, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Nonlinear System Coherence Analysis of the Surge Response of Tension Leg Platforms Subject to NonGaussian Irregular Seas," Proceedings of the Eighth International Conference on Offshore Mechanics and Arctic Engineering, Vol. 1, The Hague, The Netherlands, 167-173, March 19-23, 1989.

- **8. S. B. Kim, E. J. Powers, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Spectral Decomposition of Nonlinear TLP Sway Response to NonGaussian Irregular Seas," paper OTC 6134, Proceedings of the 21st Annual Offshore Technology conference, Houston, Texas, pp. 123-128, May 1-4, 1989.
- *9. S. W. Nam, S. B. Kim, and E. J. Powers, "Utilization of Digital Polyspectral Analysis to Estimate Transfer Functions of Cubically Nonlinear Systems with NonGaussian Inputs," Proceedings of the 1989 IEEE International Conference on Acoustics, Speech and Signal Processing, Vol. 4, Glasgow, Scotland, pp. 2306-2309, May 23-26, 1989.
- *10. E. J. Powers, Ch. P. Ritz, C. K. An, S. B. Kim, R. W. Miksad, and S. W. Nam, "Applications of Digital Polyspectral Analysis to Nonlinear Systems Modeling and Nonlinear Wave Phenomena," Proceedings of the Workshop on Higher-Order Spectral Analysis, Vail, Colorado, pp. 73-77, June 28-30, 1989.
- **11. S. B. Kim, E. J. Powers, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Nonlinear Spectral Decomposition of the Drift Response of Tethered Offshore Structures Subject to NonGaussian Irregular Seas," Proceedings of the Workshop on Higher-Order Spectral Analysis, Vail, Colorado, pp. 200-205, June 28-30, 1989.
- **12. S. B. Kim, E. J. Powers, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Applications of Recent Advances in Digital Nonlinear Time Series Analysis Techniques to TLP Model Test Data," Proceedings of the International Symposium on Offshore Engineering - BRASIL OFFSHORE '89, Rio de Janeiro, Brazil, 18 pp., August 21-25, 1989. To appear in Offshore Engineering, Pentech Press, London, 1990.
- **13. E. J. Powers, S. B. Kim, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Analysis and Interpretation of TLP Model-Test Data Using Advanced Nonlinear Signal Analysis Techniques," Proceedings of the 5th Deep Offshore Technology International Conference and Exhibition, Marbella, Spain, pp. 90-102, October 16-18, 1989.
- III. LIST OF CONFERENCE PRESENTATIONS (* denotes JSEP supported in whole or in part; ** denotes work principally supported by another grant(s)/contract(s) in which JSEP is acknowledged for its nonlinear signal processing contributions.)
 - *14. E. J. Powers, "Application of Digital Bispectral Analysis to Nonlinear Wave Phenomena," presented at the Nonlinear System Modeling and Higher-Order Frequency Response Workshop, Austin, Texas, February 4, 1989.
 - **15. M. R. Hajj, R. W. Miksad, and E. J. Powers, "On the Subharmonic Generation in a Plane Mixing Layer," Joint Spring Meeting of the Texas Sections of the American Physical Society, Houston, Texas, March 3-4, 1989.
 - **16. R. W. Miksad, M. R. Hajj, and E. J. Powers, "Effects of Mean Flow Unsteadiness on the Subharmonic Generation in Mixing Layers," paper AIAA-89-0980 presented at the AIAA Second Shear Flow Conference, Tempe, Arizona, March 13-16, 1989.

- **17. K. H. Kim, S. B. Kim, E. J. Powers, and R. W. Miksad, "Applications of Second Order Volterra Digital Filters to Low Frequency Drift Oscillation Phenomena," presented at the Eighth International Conference on Offshore Mechanics and Arctic Engineering, The Hague, The Netherlands, March 19-23, 1989.
- **18. S. B. Kim, E. J. Powers, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Nonlinear System Coherence Analysis of the Surge Response of Tension Leg Platforms Subject to NonGaussian Irregular Seas," presented at Eighth International Symposium on Offshore Mechanics and Arctic Engineering, The Hague, The Netherlands, March 19-23, 1989.
- **19. E. J. Powers and R. W. Miksad, "Polyspectral Methods," presented at the Office of Naval Research Nonlinear Ship Motions Workshop, David Taylor Research Center, Bethesda, Maryland, April 13, 1989.
- **20. S. B. Kim, E. J. Powers, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Spectral Decomposition of Nonlinear TLP Sway Response to Non-Gaussian Irregular Seas," paper OTC 6134 presented at the 21st Annual Offshore Technology Conference, Houston, Texas, May 1-4, 1989.
- *21. S. W. Nam, S. B. Kim, and E. J. Powers, "Utilization of Digital Polyspectral Analysis to Estimate Transfer Functions of Cubically Nonlinear Systems with NonGaussian Inputs," presented at the 1989 IEEE International Conference on Acoustics, Speech, and Signal Processing, Glasgow, Scotland, May 23-26, 1989.
- *22. E. J. Powers, C. K. An, S. B. Kim, R. W. Miksad, S. W. Nam, and Ch. P. Ritz, "Applications of Digital Polyspectral Analysis to Nonlinear Systems Modeling and Nonlinear Wave Phenomena," presented at the Workshop on Higher-Order Spectral Analysis, Vail, Colorado, June 28-30, 1989.
- **23. S. B. Kim, E. J. Powers, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Nonlinear Spectral Decomposition of the Drift Response of Tethered Offshore Structures Subject to Non-Gaussian Irregular Seas," presented at the Workshop on Higher-Order Spectral Analysis, Vail, Colorado, June 28-30, 1989.
- **24. E. J. Powers and R. W. Miksad, "The Use of Polyspectral Techniques to Determine Quadratic Transfer Functions for Offshore Structures," presented at the Joint ASCE/ASME Engineering Mechanics Conference, La Jolla, California, July 9-12, 1989.
- **25. E. J. Powers, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Applications of Recent Advances in Digital Nonlinear Time Series Analysis Techniques to TLP Model Test Data," presented at The International Symposium on Offshore Engineering - BRASIL OFFSHORE '89, Rio de Janeiro, Brazil, August 21-25, 1989.
- **26. E. J. Powers, S. B. Kim, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Analysis and Interpretation of TLP Model-Test Data Using Advanced Nonlinear Signal Analysis Techniques," presentation at the Deep Offshore Technology 5th International Conference and Exhibit, Marbella, Spain, October 16-18, 1989.

- **27. R. W. Miksad, M. R. Hajj, and E. J. Powers, "Experiments on Subharmonic Generation by Parametric Resonance," presented at the 42nd Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, Palo Alto, California, November 19-21, 1989.

IV. LIST OF THESES AND DISSERTATIONS

- * C. K. An, Ph.D., May 1989, "Frequency Domain Analysis of Dual-Input/Multiple Output Quadratic Systems with General Random Inputs."

B. B. Feaster, M.S., December 1988, "A Comparison of Methods for Estimating Lyapunov Exponents from Experimental Data."

V. CONTRACTS AND GRANTS

E. J. Powers and R. W. Miksad, "Applications of Frequency and Wavenumber Nonlinear Digital Signal Processing to Nonlinear Hydrodynamics Research," Office of Naval Research, Contract N00167-88-K-0049, April 22, 1988 - September 30, 1989.

E. J. Powers and R. W. Miksad, "Applications of Frequency and Wavenumber Nonlinear Digital Signal Processing To Nonlinear Hydrodynamics Research," Office of Naval Research, Contract N00014-88-K-0638, September 1, 1988 - April 21, 1991.

E. J. Powers and R. W. Miksad, "Application of Nonlinear Digital Time Series Analysis Techniques to Tension Leg Platform Model-Test Data," Texas Advanced Technology Program, TATP Grant 4604, May 1988 - August 1990.

R. W. Miksad and E. J. Powers, "An Experimental Study of the Nonlinear Dynamics of Unsteady Mixing Layers," Texas Advanced Research Program, TARP Grant 3280, May 1988 - August 1990.

E. J. Powers and R. W. Miksad, "Nonlinear System Identification of Tension Leg Platform Dynamics," Texas Advanced Technology Program, Grant No. to be announced, Jan. 1, 1990 - December 31, 1992.

R. O. Stearman and E. J. Powers, "Aeroelastic System Identification of Advanced Technology Aircraft Through Higher Order Signal Processing," Texas Advanced Technology Program, Grant No. to be announced, Jan. 1, 1990 - December 31, 1992.

CONSULTATIVE AND ADVISORY FUNCTIONS

Consultative and Advisory Functions

J. K. Aggarwal participated in the NATO Advanced Research Workshop on Multisensor Fusion for Computer Vision, Grenoble, France, June 26-30, 1989.

J. K. Aggarwal participated in the NSF Underwater Autonomous Vehicles Workshop, Tokyo, Japan, October 4-6, 1989.

J. K. Aggarwal attended and participated in the NATO Advanced Research Workshop on Sensory System for Robotics Control, Pisa, Italy, October 28 - November 3, 1989.

On February 1, 1989, T. Itoh visited Dr. E. Cohen at DARPA and made a presentation on Computer Aided Design for MIMIC Phase III program.

On February 2, 1989, T. Itoh visited Drs. V. G. Gelinovatch, G. Iafrate and B. Perlman at LABCOM, Fort Monmouth and described microwave research programs of The University of Texas at Austin.

On March 22, 1989, T. Itoh visited Drs. V. G. Gelinovatch and B. Perlman at LABCOM, Fort Monmouth and discussed several technical issues on computer aided design of microwave and millimeter-wave integrated circuits as well as microwave-optical interaction technology.

On June 19-22, 1989, T. Itoh participated in the Army Electronics Strategy Workshop at Pinehurst, North Carolina organized by Dr. J. Mink of the Army Research Office.

On July 14, 1989, T. Itoh visited NASA Lewis Research Center and presented a seminar coordinated by Drs. K Bhasin, R. Simons and R. Leonard on microwave research at The University of Texas.

T. Itoh was a panel member at the NSF Workshop on Future Research in Electromagnetics in Boston on July 27, 1989.

As a member of the Army Science Board, E. J. Powers participated in the fall meeting of the Board held in Fort Benning, Georgia, October 30-November 2, 1989. He also served on a panel of the Board charged with reviewing the Army's Tech Base Master Plan. This panel met several times at the Pentagon in late winter and early spring of 1989.

E. J. Powers presented the invited lecture, "Polyspectral Methods," at the ONR Nonlinear Ship Motion Workshop held at David Taylor Research Center, Bethesda, Maryland, April 13, 1989.

J. L. Erskine served on the Presidential Young Investigator Selection Panel of the National Science Foundation, Washington, D.C., December 12-14, 1988.

J. L. Erskine participated in a Workshop entitled "Monolayer Magnetism," sponsored by the Office of Naval Research in Berkeley Springs, West Virginia, August 14-17, 1989.

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AFWAL/MLPO
Wright-Patterson AFB, OH 45433-6533

LHM Technical Area Manager
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WRDC/MLPJ
Wright-Patterson AFB, OH 45433-6533

Naval Ocean Systems Center
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Code 56
San Diego, CA 92152

Director
Stanford Electronics Laboratories
Stanford University
Stanford, CA 94305

Professor Michael Tinkham
Department of Physics
Harvard University
Cambridge, MA 02138
(617) 495-3735

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P. O. Box 12211
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Washington, DC 20375

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RADCE/ESE
Hanscom AFB, MA 01731

Commander
U.S. Army Laboratory Command
Electronics Technology and Devices
Laboratory
ATTN: SLCET-E (Dr. Jack Kohn)
Fort Monmouth, NJ 07703-5202

Commander
U.S. Army Communications-Electronics
Command
ATTN: AMSEL-RD-C3-IR (Dr. Leon Kotin)
Fort Monmouth, NJ 07703-5204

Dr. Clifford Lau
Office of Naval Research
Code 1114
800 N. Quincy Street
Arlington, VA 22217-5000

Dr. Thomas J. Manuccia
Naval Research Laboratory
Laser Physics Branch
Code 6543
4555 Overlook Avenue, S.W.
Washington, DC 20375

Commander
U.S. Army Laboratory Command
Harry Diamond Laboratories
ATTN: SLCHD-NW-RC (Dr. James McGarrity)
2800 Powder Mill Rd
Adelphi, MD

Dr. M. L. Minges
AFWAL/MLP
Wright Patterson AFB, OH 45433

Director
U.S. Army Signals Warfare Center
ATTN: AMSEL-RD-SW-PE (Mr. James Mulligan)
Vint Hill Farms Station
Warrenton, VA 22186-5100

Mr. John L. Mullis
AFWAL/NTCA
Kirtland AFB, NM 87117

Dr. A. Nedoluha
Naval Ocean Systems Center
Code 56
San Diego, CA 92152

Dr. Yoon Soo Park
Office of Naval Research
Code 121
800 N. Quincy Street
Arlington, VA 22217-5000

Dr. Gary Prinz
Code 6635
Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375-5000

Director
Night Vision and Electro-Optics
Center
ATTN: AMSEL-RD-NV-L (Dr. Robert Rohde)
Fort Belvoir, VA

Dr. William Sander
Electronics Division
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

U.S. Army Communications-Electronics
Command
ATTN: AMSEL-RD-C3-TR-4 (Dr. Schwering)
Fort Monmouth, NJ 07703

Commander
U.S. Army Laboratory Command
Harry Diamond Laboratories
ATTN: SLCHD-S3TO (Dr. Arthur Sindoris)
2800 Powder Mill Rd
Adelphi, MD 20783-1197

Dr. Jerry Smith
Naval Weapons Center
Code 381
China Lake, California 93555

Commander
U.S. Army Communications
Center For Command, Control, and
Communications Systems -
AMSEL-RD-C3-TA-1 (Dr. Haim Soicher)
Fort Monmouth, NJ 07703-5202

Commander
Avionics Research and Development
Activity
ATTN: AAVRDA/NASA LARC (Mr. George Stech)
Mail Stop MS 268
Langley Research Center
Hampton, VA 23665

Commander
U.S. Army Belvoir R&D Center
ATTN: STRBE-ZTS (Dr. Karl Steinbach)
Fort Belvoir, VA 22060-5606

Dr. Philip Stover
AFWAL/AADR
Wright Patterson AFB, OH 45433

Dr. Michael A. Stroschio
Electronics Division
U.S. Army Laboratory Command
Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Dr. Sidney Teitler
Naval Research Laboratory
Code 6801
4555 Overlook Avenue, S.W.
Washington, DC 20375

U.S. Army Laboratory Command
Harry Diamond Laboratory
ATTN: SLCHD-ST-AP (Dr. Mary Tobin)
2800 Powder Mill Rd
Adelphi, MD 20783-1197

Commander/Director
White Sands Missile Range
ATTN: STEWS-ID-T (Mr. Robert Voss)
White Sands Missile Range, NM 88002

Dr. John Zavada
Electronics Division
U.S. Army Laboratory Command
Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Naval Weapons Center
Code 381
China Lake, CA 93555